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INFRARED TEMPERATURE SOUNDING EXPERIMENTAL STUDY

Contract No. 952037

Final Report

Covering Period 22 August 1967 to 19 April 1968

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Introduction

This Final Report covers research performed during the past eight months on theoretical aspects of an infrared temperature sounding experiment. The primary goal of this research has been to develop and improve methods of analysis which will be of direct use in the reduction of infrared spectral radiance measured with instrumentation being developed at the Jet Propulsion Laboratory. Indeed, the theoretical analyses performed under this contract in some cases places restrictions on the instrumentation.

Emphasis has been placed on the calculations of water vapor transmittance in the 6.3μ region and on the inclusion of absorption due to CO, N_2, N_2O and H_2O on the CO_2 absorption in the 4.3μ region. A considerable amount of effort was placed on detailing the "Radiance" computer program and on the problem of the uniqueness of solution of the radiative transfer equation applied to a simple 2-layer model.

Conversion of Computer Programs

During the first month of this contract a great deal of time was spent converting two major computer programs to an appropriate language for use on the IBM 360/75 system. One computer program computes the spectral radiance in the region of the 4.3μ CO_2 band and the other program inverts the equation of radiative transfer and thereby determines the vertical temperature distribution by operating on the measured spectral distribution of radiance. These computer programs now work on the 360/75 system and produce similar results to those obtained on the IBM 7094 at J.P.L. The programs run faster on the 360/75 system and should be more accurate due to the use of double precision for all operations.

Variable Pressure Levels

It was apparent in some experiments with the "inversion" program that convergence did not always occur. This problem was investigated along with the feasibility of allowing the pressure levels at which the temperature is sought to be variable. A system was found which allows the pressure to vary such that approximatel· alf of the area under the weighting function curve ($Bd\tau/d\ln p$) lies on either side of the pressure level in question at each iteration. After several iterations it was found that the pressure levels must be held fixed in order to avoid convergence difficulties. This system works quite well as far as convergence is concerned, but the major problem now is to discover whether a satisfactory result can be obtained when dealing with real data. This variable pressure level technique has been made an integral part of the "inversion" program.

Inversion "Games"

In order to objectively test the developed method for the inversion of the radiative transfer equation, it was agreed that some inversion "games" would be played. Dr. C. B. Farmer would pick a temperative profile and compute the spectral distribution of radiance with the "Radiance" computer program at J. P. L. These results would be mailed to me and I would use the "Inversion" program and whatever other judgment seemed reasonable to determine the temperature profile and the surface temperature. A comparison of the initial and inferred temperatures would constitute an objective test of the mathematical inversion procedure. It should be noted that this test does not consider either experimental or theoretical errors.

In comparing the inferred and initial temperature profiles it was decided that it is most meaningful to compare the mean temperature in the atmospheric layer in question. In general the derived profile is obtained with much less height resolution than the known temperature profile. The known temperature profile should be averaged according to Eq. 1 for purposes of comparison.

$$\overline{T} = \frac{\int T_{ij} d(\ln p)}{\int d(\ln p)} \quad \frac{\sum T_{ij} \Delta \ln p}{\sum \Delta \ln p} \tag{1}$$

T_{ij} is the simple mean temperature in the atmospheric layer bounded by p_i and p_j . If $(p_i - p_j)/p_j$ is small (say $\angle$ 0.2), Eq. 1 can be replaced by Eq. 2. Equation 2 is also used in the highest atmospheric layer as $p_j \rightarrow 0$

$$\overline{T} = \frac{\int T_{ij}\, dp}{\int dp} \qquad \frac{\sum' T_{ij}\, \Delta p}{\sum' \Delta p} \tag{2}$$

A plot of the results of the first "Inversion" game is given in Fig. 1. The curve represents the original temperature profile used by Dr. Farmer in the initial computation of the spectral distribution of radiance. The vertical lines refer to the derived temperatures, the lengths of the lines corresponding to the atmospheric layers for which the indicated temperature values apply. The results of this test are encouraging, but many more such tests should be made before drawing any real conclusions from this one example.

A second "test" of the inversion scheme was made with Dr. Farmer providing a spectral distribution of radiance to which I applied the inversion scheme. The results are shown in Fig. 2 and can be seen to give good agreement, but not quite as good as the first "test". The vertical lines marked "non-isothermal" and "isothermal" refer to the initial approximation used in the inversion scheme. The "non-isothermal" case did not converge quite as well as the "isothermal" case.

In both of these "tests" the effect of allowing the pressure levels to vary can be seen. In both the lowest part of the atmosphere and in the highest level sounded there is better height resolution than there is near the tropopause. This is a reflection of the small amount of information arising from near the tropopause as is evident from an examination of the weighting functions ($B\, d\tau / d \ln p$).

Atmospheric Absorption Due to H_2O

A great deal of effort was placed on computing transmittance due to H_2O. The water vapor spectral data published by Gates, et al[1] and Benedict and Calfee[2] was purchased (punched on IBM cards). These data cover the 1.9, 2.7, and 6.3μ bands of H_2O. It was originally intended to concentrate on the 1.9 and 2.7μ bands, but due to the removal of the near infrared measurements from the experiment, the major concentration was on the 6.3μ band. It should be noted that the computer program which was developed is applicable to all three bands with appropriate changes in input data. A listing of the computer program is included in the Appendix and a description of the calculations follows:

After reading all spectral lines in a given spectral interval and specifying the spectral resolution for which the calculations are to be made we read a table which describes a model atmsophere in terms of pressure, temperature, and water vapor abundance. The program can accept a model atmosphere defined by at most 20 atmospheric levels. The basic calculation is described by Eq. 3.

$$\bar{\tau}_{\Delta\nu} = \exp\left(- \frac{1}{\Delta\nu} \sum_i W_i \right) \tag{3}$$

where $\Delta\nu$ is the spectral resolution and W_i is the equivalent width of the i^{th} spectral line in the interval $\Delta\nu$. The W_i are given by Eq. 4.

$$W_i = 2\pi \alpha_i L (U_i) \tag{4}$$

where $L(U_i)$ is the Ladenberg and Reiche function, $U_i = \frac{S_i m}{2\pi \alpha_i}$, S_i and α_i are line intensity and the half width respectively of the i^{th} spectral line, m is the quantity of absorbing gas in the atmospheric path under consideration.

The program computes the transmittance from the top of the atmosphere to all pressure levels specified in the atmospheric model. The integration through the inhomogeneous atmosphere is accomplished by a Curtis-Godson approximation as described by McClatchey[3].

In additior to the transmittance, the quantities $B(\bar{\nu}, T)$, $d\tau/d\ln p$, $B(\bar{\nu}, T)\left[d\tau/d\ln p\right]$ are all computed for each atmospheric layer.

Some results of the application of this computer program to some realistic model atmospheres follow: Table 1 presents the three model atmospheres studied. Arctic, midlatitude and tropical models were based on data and graphs presented in the "Handbook of Geophysics and Space Environments."[4] It is hoped that these models will cover the range of conditions usually encountered in the terrestrial atmosphere. Figure 5 display the quantity $d\tau/d\ln p$ for the three models. Figures 6-8 present $B(d\tau/d\ln p)$. These calculations ere made for 20 cm^{-1} intervals. I have plotted the results for the spectral intervals most nearly corresponding to the wavelengths given in the new experiment proposal and enclosed with the letter from John Shaw dated Oct. 14, 1967. A glance at these figures indicates that the interval centered at 1890 cm^{-1} should be at a lower frequency. According to calculations made with this program, the following spectral locations will produce the best information for the determination of the vertical water vapor distribution: 1640-1660 cm^{-1}, 1780-1800 cm^{-1}, 1840-1860 cm^{-1}, 1880-1900 cm^{-1}, 1960-1980 cm^{-1}, 2020-2040 cm^{-1}.

Figure 9 presents a calculated spectrum of the entire atmosphere covering a portion of the region in which the temperature sounding data is to be obtained. We currently expect to use radiance values from 2220-2360 cm^{-1} in the temperature sounding analysis. Figure 9 suggests that we may introduce errors near the ground if we do not appropriately account for atmospheric water vapor.

The computer program developed to compute water vapor transmission was tested for agreement with the laboratory data of Burch, et al[5] with the results shown in Figures 10 and 11. Figure 10 shows the results of applying the program to four cases identical to those run by Burch, et al. The laboratory results of Burch et al are given in Figure 11. The two stronger absorbing cases are in good agreement, but the two weaker absorbing cases appear to be considerably in error. Additional tests must be made in order to establish the accuracy of the computer program for all ranges of absorption of interest in the atmosphere.

Table 1

Pressure (mb)	Temperature (°K)	Water Vapor (Pr. cm. above p)
	Arctic Model	
6.9	197.2	0.0
8.0	197.2	0.0001
11.3	197.2	0.0002
15.9	197.2	0.0004
22.5	197.8	0.0005
31.7	199.0	0.0006
44.6	200.2	0.0007
62.6	201.4	0.0008
88.0	204.0	0.0009
122.0	206.9	0.0010
169.0	209.9	0.0011
234.0	212.9	0.0017
321.0	217.9	0.0030
436.0	228.9	0.0070
584.0	240.0	0.0222
772.0	250.9	0.0762
1014.0	249.2	0.1698
	Midlatitude Model	
10.1	227.0	0.0
11.7	227.0	0.0002
15.9	225.0	0.0007
21.5	223.0	0.0011
29.3	221.0	0.0015
40.0	219.0	0.0019
54.7	217.0	0.0023
75.0	217.0	0.0026
103.0	217.0	0.0029
141.0	217.0	0.0033
193.0	217.0	0.0041
264.0	223.0	0.0063
356.0	236.0	0.0213
472.0	249.0	0.0923
616.0	262.0	0.2980
795.0	275.0	0.8186
1013.0	88.0	1.9410

Pressure (mb)	Temperature (°K)	Water Vapor (Pr. cm. above p)
	Tropical Model	
10.1	234.5	0.0
11.7	232.3	0.0002
15.9	227.9	0.0007
20.0	219.2	0.0011
40.0	214.6	0.0013
60.0	206.7	0.0014
80.0	198.8	0.0015
100.0	197.0	0.0016
150.0	210.3	0.0018
200.0	223.6	0.0025
265.0	236.7	0.0080
357.0	250.1	0.0334
472.0	263.5	0.1370
617.0	276.9	0.4480
747.0	287.0	0.9470
795.0	287.7	1.3500
1013.0	300.0	4.2100

Absorption Due to N_2O, CO, N_2, H_2O Near 4.3μ

After the February 1967 balloon flight, a careful re-evaluation of the theoretical calculations was made. It was concluded that the effects of N_2O, N_2, CO, and H_2O absorption should be included in the 4.3μ CO_2 region. At the time of the February 1967 balloon flight only CO_2 and N_2O were considered in the spectral region used for temperature sounding. These other molecules were added and the lowest frequency for which calculations were made was reduced from 2180 cm^{-1} to 2150 cm^{-1}. It was hoped that some lower frequencies would be useful in determining atmospheric temperature near the surface in greater detail. The CO transmittance was computed according to the method outlined by Gray and McClatchey[6]. The N_2 absorption coefficient was obtained from Figure 12, provided by Dr. C. B. Farmer. The molecular abundances used in the calculations are as follows:

CO_2	-	256 $(cm\text{-}atm)_{STP}$
N_2O	-	0.22 $(cm\text{-}atm)_{STP}$
CO	-	0.06 $(cm\text{-}atm)_{STP}$
N_2	-	0.781 fraction by volume.

All of these molecules were assumed to be uniformly mixed in the atmosphere. The introduction of water vapor had to be handled in a much different manner, because the actual or assumed distribution must be introduced with each calculation. Figure 13 gives the weighting functions computed with the improved computer program for the indicated frequencies. The water vapor distribution used in connection with these calculations is the one entitled "Midlatitude Model" in Table 1. There is very little difference between these functions and previously computed ones except at the lowest frequencies. The curves for $\nu < 2275$ are shifted upward to some extent.

These new calculations indicate that only a very slight correction to previous radiance calculations for $\nu < 2240$ will be necessary. Thus, the neglect of these molecules is not responsible for the discrepancy in the February 1967 balloon flight results. For lower frequencies, a significant correction is required and the greatest effect results from the addition of water vapor. Figures 14 and 15 show the results of the transmission before and after the inclusion of additional absorbing molecules.

Discussion of Calculations Made in the Radiance Program

A complete discussion of the calculations performed in both the Radiance and Inversion computer programs was intended as part of the work to be completed under this contract. This job has not yet been accomplished for the Inversion program, but it has been done for the Radiance program and the discussion follows (A listing of the Radiance program is included in the Appendix):

The atmosphere is divided into a certain number of layers for the purpose of numerical computations. The pressure, temperature and amount of water vapor associated with the boundary of each layer (i. e. each level) are required input data. Water vapor is read in as the amount above a specified pressure level in units of precipitable centimeters.

The large loop (statement No. 1540 to 2490) refers to transition number. Each 5 cm^{-1} interval has a set of vibrational transitions associated with it. The number of transitions runs from 1 to 25 depending on the spectral interval. Statements No. 1670 to 1750 compute the fictitious quantum number associated with the specified frequency. I say fictitious because it will in general be fractional. We are solving a fourth order algebraic equation here as given below for the quantum number m.

$$\nu = \nu_o + Am + Bm^2 + Cm^3 + Dm^4 \qquad (5)$$

Statements No. 1790 to 1910 determine the matrix element of the dipole moment appropriate to the specified transition.

Statements No. 2080 to 2470 specify the loop in which the transmission for each vibrational transition and from each pressure level to space is computed. Statements No. 2190-2210 define the line intensity. Statements No. 2350-2380 compute $\int S dm$ and $\int S \alpha dm$ according to Eqs. 6.

$$\int S \, dm \simeq \sum_{i=1}^{kk} S_i \, c \Delta p_i$$

$$\int S \alpha dm \simeq \sum_{i=1}^{kk} S_i \alpha_{oi} \frac{(P_i + P_{i+1})}{2} \sqrt{\frac{T_o}{T}} \, c \Delta p_i \qquad (6)$$

where

S_i is the intensity at the central frequency of the interval under consideration of the i^{th} vibrational transition,

α_{oi} is its half-width at STP,

T_o is 298°K,

P_i and T_i are pressure and temperature at the i^{th} atmospheric levels respectively.

In this way an equivalent homogeneous atmosphere is defined which is used in the subroutine TISR in order to establish the transmission. The subroutine TISR computes the transmission due to one vibrational transition according to Eq. 7.

$$\tau_i = 1 - \sinh\beta \int_o^Y I_o(u) \exp(- U \cosh\beta) \, du \qquad (7)$$

where $\beta = \frac{2\pi\alpha}{d}$ and $y = \frac{Sm}{d \sinh \beta}$ and $I_o(u)$ is the Bessel function of imaginary argument and order zero. Further details are outlined in Reference 6.

After computation of the transmission due to each vibrational transition, the resulting transmission is computed according to Eq. 8.

$$\tau = \prod_i \tau_i \tag{8}$$

This operation is performed in statement No. 2650.

The WATER subroutine computes the transmission due to water vapor according to the statistical model using the actual line parameters for each spectral interval from the work of Benedict and Calfee[2].

The nitrogen absorption coefficient is a slowly varying function of frequency. Therefore, one absorption coefficient is read in for each 5 cm^{-1} interval and the transmission is computed according to Eq. 9.

$$\tau_{N_2} = \exp(- c\, k_\nu \int p\, H dp). \tag{9}$$

where $c = N_2$ concentration

H = scale height

The final transmission is then given by Eq. 10.

$$\tau = \prod_i \tau_i \, (\tau_{N_2})\, (\tau_{H_2O}) \tag{10}$$

where the i transitions include CO_2, N_2O, and CO. The final two multiplications occur in statements No. 2750 and 2760.

Having computed the transmission from each specified pressure level to the lowest input pressure level, we are now in a position to compute the radiance. Equation 11 is evaluated between statement No. 2940 and 3600.

$$I_{\nu} = \int B_{\nu} \, d\tau_{\nu} + B(T_g) \, \tau_{\nu_g} \tag{11}$$

In the same part of the program, the quantity $d\tau / d\ln p$ and $(d\tau/d\ln p)B$ are also computed and later printed out as additional information. If the atmosphere between two pressure levels is isothermal or if $\Delta\tau$ is very small (in all cases recently tested $\Delta\tau < 0.2$ is very small), the Planck function is evaluated at the mean temperature of the included layer and no further division of the scale is made in the course of the numerical integration. (See statements No. 3030-3080) Under all other circumstances, the temperature is assumed to vary logarithmically with pressure, the $\Delta\tau$ interval is divided into 5 parts, and a logarithmic temperature interpolation is made. The resulting additional intervals are then used in the numerical integration. (See statement No 3090-3290).

Statement No. 3311 to 3319 are required in order to normalize $d\tau/d\ln p$ and $(d\tau/d\ln p)B$.

Between statements No. 3400-3500, weights (TW(K)) are defined in such a way that $\sum_k W_k B_k$ gives the "best" approximation to the intensity. The trapezoidal rule in general gave an underestimate to the intensity. Simpsons rule requires a mid-point temperature and transmission to be defined, but this is unacceptable in the inversion r^utine. Thus the ratio of the Simpson's rul· to the trapezoidal rule result is used for each layer. In this way, the resulting weights become exact if the B vs τ relationship is nonlinear. The main point of all this is that we <u>must</u> be able to express I_ν as $\sum_k W_k B_k$ if the current inversion scheme is to apply where the K items in the sum represent the K atmospheric levels.

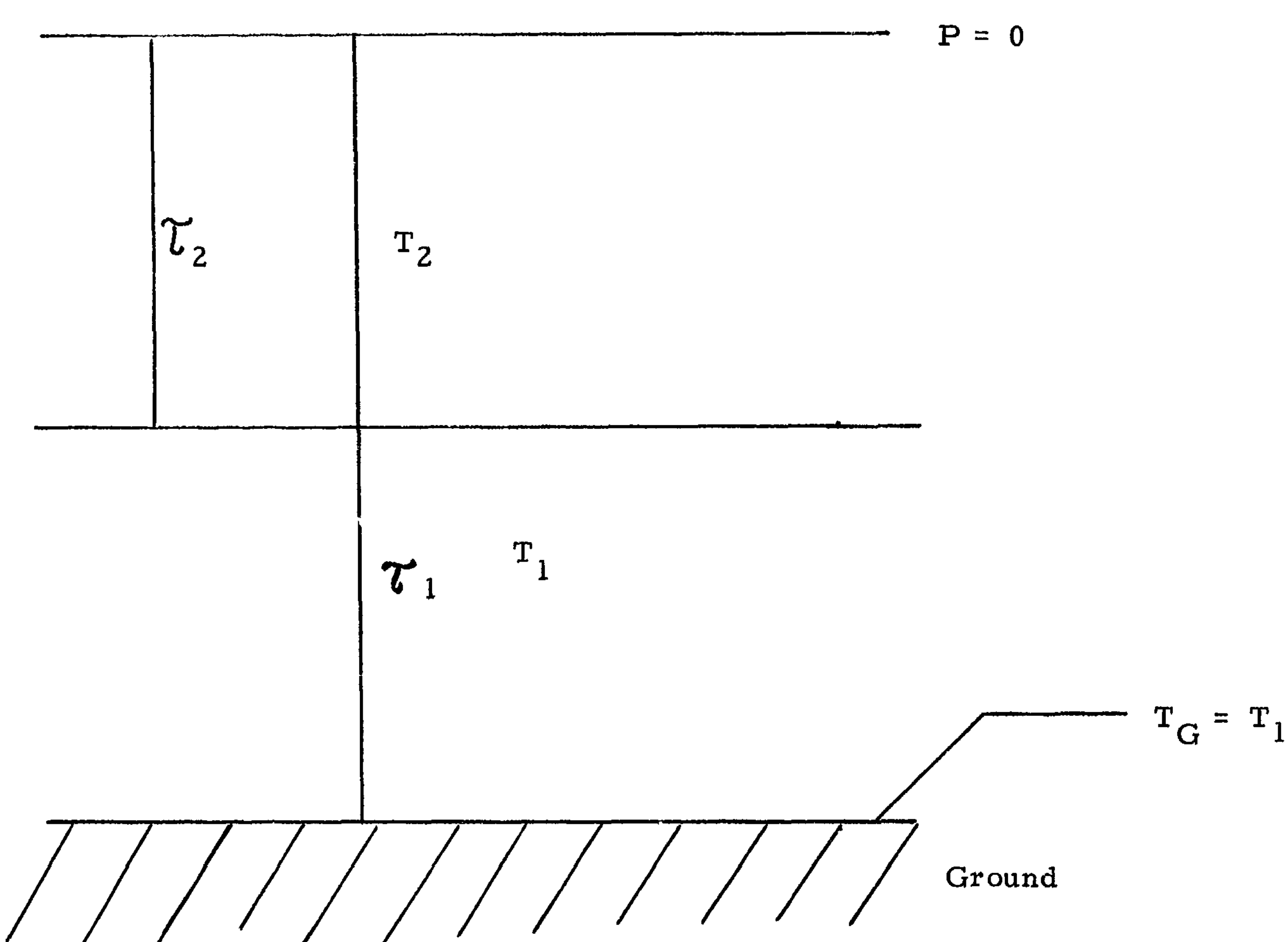
The weights to be used in the inversion program with the first approximation are those computed here.

The final 5 cm^{-1} intensity is computed in statement 3600.

From statement No. 3790 to 3950 a triangular slit function with 20 cm^{-1} half width is convolved with both the intensity and with the weights. The new mean weights are then adjusted so that we still have $\bar{I} = \sum \overline{W}_k B_k$ even though $\bar{I}$ and $\overline{W}$ are now mean values. The results are called FCP015 and AVWAT.

Uniqueness of Solution

The problem of uniqueness was examined in connection with the inversion of the equation of radiative transfer. In order to gain some insight into the problem, a simple two layer atmosphere was considered. The ground temperature was assumed to be identical to the lowest atmospheric layer. The model is best described by examining the following figure.



Let us write the equations relative to this two-layer model.

$$I(\nu_1) = B(\nu_1, T_1)\left[\tau_2(\nu_1) - \tau_1(\nu_1)\right] + B(\nu_1, T_2)\left[1 - \tau_2(\nu_1)\right] + B(\nu_1, T_1)\,\tau_1(\nu_1)$$
$$I(\nu_2) = B(\nu_2, T_1)\left[\tau_2(\nu_2) - \tau_1(\nu_2)\right] + B(\nu_2, T_2)\left[1 - \tau_2(\nu_2)\right] + B(\nu_2, T_1)\,\tau_1(\nu_2) \qquad (12)$$

At 4.3μ we have $B(\nu, T) = 2hc^2\nu^3 \exp(-hc\nu/kT)$, so Eqs. 12 become:

$$I(\nu_1) = A_1(\nu_1)\,y_1 + A_2(\nu_1)\,y_2$$
$$I(\nu_2) = A_3(\nu_2)\,y_1^{\alpha} + A_4(\nu_2)\,y_2^{\alpha} \qquad (13)$$

where

$$A_1(\nu_1) = 2hc^2\nu_1^3\,\tau_2(\nu_1) \qquad A_2(\nu_1) = 2hc^2\nu_1^3\left[1 - \tau_2(\nu_1)\right]$$

$$A_3(\nu_2) = 2hc^2\nu_2^3\,\tau_2(\nu_2) \qquad A_4(\nu_2) = 2hc^2\nu_2^3\left[1 - \tau_2(\nu_2)\right]$$

$$y_1 = \exp(-hc\nu_1/kT_1) \qquad \text{and} \qquad \alpha = \nu_2/\nu_1$$

Solving the first Eqs. 13 for y_2 and inserting the result in the second, we have:

$$I(\nu_2) = A_3(\nu_2)\,y_1^{\alpha} + A_4(\nu_2)\left\{\frac{I(\nu_1) - A_1(\nu_1)\,y_1}{A_2(\nu_1)}\right\}^{\alpha} \qquad (14)$$

Rearranging Eq. 14, we obtain Eq. 15

$$\left\{\frac{I(\nu_2) - A_3(\nu_2)\, y_1^{\alpha}}{A_4(\nu_2)}\right\} = \left\{\frac{I(\nu_1) - A_1(\nu_1)\, y_1}{A_2(\nu_1)}\right\}^{\alpha} \tag{15}$$

Let us now drop the subscript on y and define some new quantities. Let the left-hand function be called f(y) and the right-hand function be g(y).

$$f(y) = A - B y^{\alpha} \qquad\qquad g(y) = (C - D y)^{\alpha} \tag{16}$$

We would like to know how many points of intersection these two functions have. Recognizing that $\alpha = p/q$ where p and q are integers, we can write Eqs. 16 as follows:

$$[F(y)]^{q} = y^{p} \qquad\qquad [g(y)]^{q} = (C - D y)^{p} \tag{17}$$

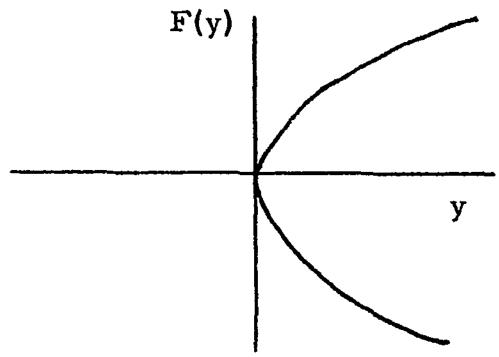
where we have put $F(y) = \frac{A-f(y)}{B}$. We must establish the form of these functions and the possibility of intersections such that f(y) = g(y).

The function, f(y), has an infinite slope at y = 0 , whereas the function g(y) has an infinite slope at y = C/D. It is clear that g(y) is the same kind of function as f(y), but displaced. Consider the first of Eqs. 17. From a purely mathematical point of view, the following possibilities exist (a diagram is drawn to show F(y) for each case):

I.) $y > 0$

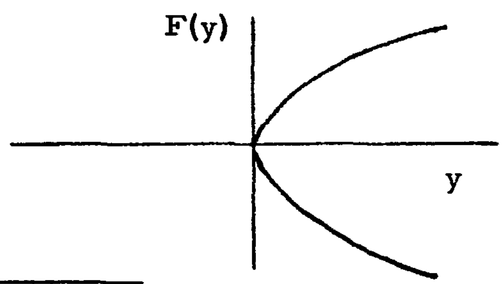
p even

q even



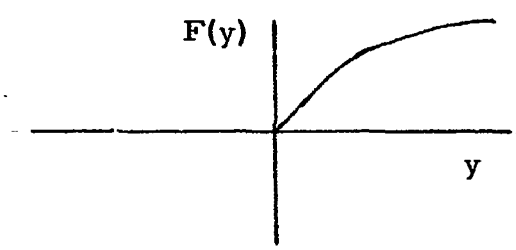
p odd

q even



p odd

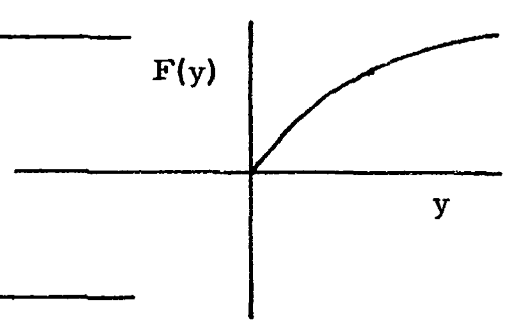
q odd



The lower branch is missing here because an odd root of a positive real number will include only one real root - the positive one. The remaining roots are complex.

p even

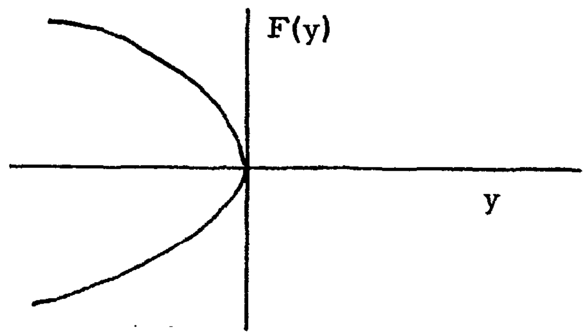
q odd



II.) $y < 0$

p even

q even



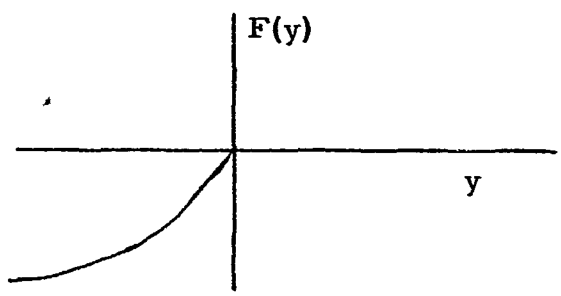
p odd

q even

all solutions will be complex for this case.

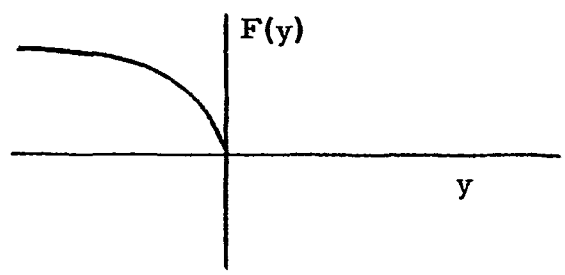
p odd

q odd



p even

q odd



In general we see that some parts of the curves shown above will be formed depending on the values of p and q and whether y is positive or negative. A similar displaced set of curves is expected for the function $g(y)$. The curves shown in Figure 16 demonstrate the situation (Relate points indicated to the functions expressed in Eqs. 16). Recalling that $y = \exp(-hc\mu/kT)$, it is clear y can never physically be negative.

Thus, we can reject all such solutions. Upon examining Eq. 13 and Eq. 16, we see that g(y) is identical with y_2 . Therefore, when g(y) is negative, T_2 must be imaginary. Thus, physically realizable solutions can only occur in the upper right-hand quadrant of Figure 16. More than one solution can only occur if f(y) intersect the y axis at $y > C/D$.

We have $f(y) = A - By^2 = 0$. Therefore, the point of intersection is $y = (A/B)^{1/2}$, and the condition that must be met in order for more than one solution to exist is $(A/B)^{1/2} > C/D$. Inserting the above definitions for A, B, C, and D, we have

$$\left(\frac{I(\nu_2)}{k\,\nu_2^3\,\tau_2}\right)^{1/\nu_2} > \left(\frac{I(\nu_1)}{k\,\nu_1^3\,\tau_1}\right)^{1/\nu_1} \tag{18}$$

where $k = 2hc^2$. Equation 18 provides us with a function of ν which can be plotted. If $\left[\frac{I(\nu)}{k\,\nu^3\,\tau(\nu)}\right]^{1/\nu}$ is a monotonic function such that this inequality can never be met, the solution to this 2-layer problem must be unique. Otherwise, a regime of non-uniqueness exists. This function has been computed for various values of temperature and for the $\tau(\nu)$ distributions computed in the Radiance program. The results indicate that the inequality of Eq. 18 will not apply except occasionally in adjacent 5 cm^{-1} spectral intervals. Thus, my conclusion is that in practice the solution to this problem is unique. It remains to be shown whether or not a similar analysis can be applied to an n-layer atmosphere.

Effect of Cloud Cover on Temperature Sounding

An investigation into the effects of partial cloud cover on the temperature sounding experiment has begun. The Radiance program has been used to compute the expected spectral distribution of radiance from a sky with 20% 40% , 60% , and 80 % cloud cover at the 800 mb, 500 mb, and 200 mb pressure levels respectively. This investigation is not yet complete. It remains to take these spectral radiance distributions and use them as input in the Inversion program in order to establish the effect of clouds on the temperature profile as inferred under the assumption of clear skies. We can say that the effect of clouds at 800 mb is very small indeed, and that the effect of 20% cloud cover at 500 mb or 200 mb makes a maximum radiance error of 10 % at the lowest frequency used in the temperature sounding. At all the other frequencies the effect is even less. The curves of spectral radiance are given in Figures 17, 18, and 19.

Meetings Attended

1. Specialist Conference on Molecular Radiation in Huntsville, Alabama (October 1967). A brief talk on the JPL experiment was given.

2. Optical Society Meeting at Detroit, Mich. (October 1967). Due to a communications problem, I was not informed in time of the cancellation of an experimenters meeting. However, I attended all relevant sessions of the Optical Society Meeting.

3. A meeting was arranged between D. Wark, H. Fleming, M. Chahine and J. Shaw at ESSA in Suitland, Maryland (December 1967). The theoretical treatment of the inversion problem developed at the Weather Bureau was discussed.

4. The Third Interdisciplinary Workshop on Inversion of Radiometric Measurement at Tallahassee, Florida (February 1968). I presented a 30 minute talk on the 4.3μ temperature sounding experiment.

Bibliography

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APPENDIX

A. Radiance Program Variables

A (I)	$B_i' + B_i''$ (see reference No. 1)
ABSN2 (I)	Absorption coefficient due to N_2 in the I^{th} spectral interval
ACO	CO abundance in $(cm\text{-}atm)_{STP}$ in a vertical column
ACO2	CO_2 abundance in $(cm\text{-}atm)_{STP}$ in a vertical column
AINT	The same as FCPO15
ALCO	Half-width at 1 atm. of CO in cm^{-1}
ALCO2	Half-width at 1 atm. of CO_2 in cm^{-1}
ALN2O	Half-width at 1 atm. of N_2O in cm^{-1}
AN2	Fraction by volume of N_2 in the atmosphere
AN2O	N_2O abundance in $(cm\text{-}atm)_{STP}$ in a vertical column
ASIMP (K)	The value of $\int B d\tau$ based on Simpson's rule
ATRAP	The value of $\int B d\tau$ based on trapezoidal rule
AVWAT	A weighting function defined to give the correct I_ν after convolution with the triangular slit function
B (I)	$B_i' - B_i''$ (see reference No. 1)
BDHD (I)	The frequency (in wavenumbers) of the bandhead of the I^{th} vibrational transition

BDP (I)	The rotational constant of the lower state (see reference No. 1)
BIGA (I)	Defined in program
BIGD (I)	The line spacing of the rotational lines belonging to the I^{th} vibrational transition
BLAK (JFNU, K)	The black body function corresponding to the K^{th} atmospheric level and the JFNU frequency
BOTNU	The lowest frequency of a major frequency interval
C (I)	$-2\,(D_i'' + D_i')$ (see reference No. 1)
COS 9	A number which can take the finite solid angle of view into account. Usually this will be = 1.0.
D (I)	$-(D_i' - D_i'')$ (see reference No. 2)
DDP (I)	The centrifugal stretching constant of the lower state. (see reference No. 1)
DELSM	Defined in program
DELTNU	The frequency sub-internal to be used within the major frequency interval. (This should be 5 cm^{-1} unless program is reorganized).
DFLUX	The intensity emitted by a particular layer of the atmosphere at a given frequency
DIF	An increment on the transmission axis. If $\Delta\tau >$ DIF, a logarithmic pressure interpolation is performed before doing the $\int B\,d\tau$ integration. If $\Delta\tau <$ DIF, a simple linear interpolation is made.
DIFR	Defined in program
DPNU (I)	The total energy (in wavenumbers) of the lower state
DPNUR (I)	The rotational energy (in wavenumbers) of the lower state for the I^{th} vibrational transition

DPNUV (I)	The vibrational energy (in wavenumbers) of the lower energy state
DPQU (I)	Energy level identification for lower state
DTDP (K)	The value of $d\tau / d \log_{10} p$ for the atmospheric layer between K and K + 1
DTDPB (K)	The value of $(d\tau / d \log_{10} p)$ B for the atmospheric layer between K and K + 1
FNU	Frequency (in wavenumbers)
FCPO15	The intensity after being convolved by a triangular slit function
GBLAK	Black body function corresponding to the ground temperature
IH2O	Number of water vapor lines read into the program
IINT	A running index which counts the number of major intervals (A major frequency interval includes several 5 cm^{-1} intervals)
INU	Number of 5 cm^{-1} spectral intervals over which the program is valid
ITOT	Total number of vibrational transitions of CO_2, N_2O and CO considered in the program
ITP	The number of levels into which the atmosphere is divided for all numerical computations
JFNU	A frequency index which corresponds to a specific frequency between 2150 and 2375 cm^{-1}
JTOT	Number of vibrational energy levels involved in all molecular transitions of CO_2, N_2O, CO
KNU	Defined in program
LEVL	The number of divisions to be made within $\Delta\tau$
NDP	Index associated with the lower state of a vibrational transition

NDUMMY (J)	A dummy variable which numbers the energy level data
NNT	The total number of vibrational frequencies considered in a given 5 cm^{-1} spectral interval
NP	Index associated with the upper state of a vibrational transition
NT (I, J)	The J vibrational transitions valid in the I^{th} 5 cm^{-1} spectral interval
NTOT (I)	The total number of vibrational transitions in the I^{th} 5 cm^{-1} interval
NTYPE (I)	Determines whether the transition is for a normal isotope or for one of several less abundant isotopes
NUMINT	The number of major frequency intervals for which calculations are to be made. (A major frequency interval includes several 5 cm^{-1} intervals)
NZP	Defined in program
P (I)	The pressure at the I^{th} atmospheric level in atmospheres
PA	Average pressure in a particular atmospheric layer
PNUV (I)	The frequency of the lower state (in wavenumbers)
PPNU (J)	The energy levels expressed in wavenumbers
PPNUV (I)	The frequency of the lower state (in wavenumbers)
PQU (I)	Energy level identification for upper state
QU (J)	Energy level identification
S	Line intensity
SEC	The secant of the zenith angle
SM (I)	Rotational quantum number at frequency, FNU, due to the I^{th} vibrational transition

SMO	An initial estimate of the rotational quantum number (m_o) based on A(I) and B(I) only
T (I)	The temperature at the I^{th} atmospheric level in °K
TFLUX	The total intensity emitted by the atmosphere at a given frequency
TG	The ground temperature in °K
TOPNU	The highest frequency of a major frequency interval
TRANS (K)	The transmission from the K^{th} pressure level to the level of measurement
TRAN1 (K, I)	The transmission between the K^{th} atmospheric level and the level of measurement due to the I^{th} vibrational transition
TRN2	The transmission due to N_2
TS	The mean temperature of a particular atmospheric layer
TW (K)	A weighting function defined such that $\sum TW \times B = I_\nu$
WAT (I)	The total amount above of H_2O the I^{th} atmospheric level expressed in precipitable centimeters
ZERONU (I)	The central frequency for the I^{th} vibrational transition
ZK (I)	The relative strength of the various vibrational transitions
ZKI (I)	Defined in program

All other names of variables appearing in the Radiance Program are defined there and are assumed to be sufficiently well identified so as to require no further explanation.

SUBROUTINES

TISR	Computes transmission according to random Elsasser model. A mathematical discussion is given in Reference 1.
WATER	Computes transmission due to water vapor by means of the random model. Line positions, half-widths, and intensities are taken from the work of Benedict and Calfee (Reference 3)

B. Radiance Program Listing

```
      IMPLICIT REAL*8 (A-H,O-Z)
C
C     L6031 R4132300000  7230  WEINSTEIN/MCCLATCHY
C     MOD 12/19/67
CEAD  PROGRAM CALCULATES RADIATIVE INENSITY 2150-2350
C     TRIANGULAR SLIT FUNCTION USED TO AVERAGE INTESITY
C     NO EXPONETIAL INTEGRAL USED
C     NO SOLID ANGLE INTEGRATION
C     CURTIS-GODSON APPROX LINE-BY-LINE USED
C
      DIMENSION BIGA(99),SM(99)
      DIMENSION BIGD(99),DPNU(99)
      DIMENSION DPNUV(99),PPNU(140)
      DIMENSION QU(140),DPQU(99)
      DIMENSION PQU(99),PNUV(99)
      DIMENSION ZK1(99),DPNUR(99)
      DIMENSION TRANS(40)
      DIMENSION DBLAK(40),BDHD(99)
      DIMENSION ZERONU(99),A(99)
      DIMENSION B(99),C(99)
      DIMENSION D(99),BDP(99)
      DIMENSION DDP(99),ZK(99)
      DIMENSION DTAU(40),ASIMP(40)
      DIMENSION ATRAP(40),TW(40)
      DIMENSION TINT(50),PRES(40)
      DIMENSION APRES(40),FBLAK(40)
      DIMENSION DTOP(40),DTOPB(40)
      DIMENSION TRAN1(40,99)
      DIMENSION AWT(50,40),BLAK(50,40)
      DIMENSION AVWAT(50,40)
      DIMENSION EXPNT(40),ABSN2(50)
      DIMENSION LCOUNT(100),NTYPE(99),NTOT(50),NT(50,24)
      DIMENSION TRH2O(40)
      COMMON/H2O/SNU(450),X(450),ALH2O(450),EDP(450),P(40),T(40),WAT(40)
      NAMELIST/QABPR/ABSN2
C
      CALL MIBCOM
      READ(5,1961) JTOT,ITOT,INU,IH2O
 1961 FORMAT(4I4)
C
C     READ IN ENERGY LEVEL DATA
      DO 5 J=1,JTOT
    5 READ (5,6)NDUMMY,QU(J),PPNU(J)
C
    6 FORMAT (I6,8X,A6,F10.2)
      WRITE (6,7)
    7 FORMAT (52H1 STATE       QUA.IS.                                //)
C
      DO 1964 N=1,JTOT
 1963 FORMAT (1H I5,8XA6,F10.2)
 1964 WRITE (6,1963)N,QU(N),PPNU(N)
C
      READ(5,8) BND
    8 FORMAT(F10.0)
      WRITE(6,9) BND
    9 FORMAT(9H0BOUND = F10.0)
      WRITE (6,10)
   10 FORMAT (117H1TRA   QUA,NO. IS. NTYPE  ZERONU       PNUV       DPNUV
```

```
     1 A            B            C            D          BDP         DDP          ZK   //)RAD00580
C
C         READ IN DATA ON VIBRATIONAL TRANSISIONS--I LESS THAN 41 IS FOR   RAD00590
C         I GT 40 BUT LT 94 IS FOR N2O, I GT 93 IS FOR CO.           CO2
          DO 15 I=1,ITOT
          READ (5,11)K,NP,NDP,NTYPE(I),A(I),B(I),ZK(I),C(I),D(I),BDP(I),DDP RAD00600
         1I)                                                          RAD00610
   11 FORMAT (4I3,3F8.5,2E9.2,F8.5,E9.2)                               RAD00620
          PQU(I)=QU(NP)                                                RAD00630
          DPQU(I)=QU(NDP)                                              RAD00640
          PNUV(I)=PPNU(NP)                                             RAD00650
          DPNUV(I)=PPNU(NDP)                                           RAD00660
          ZERONU(I)=PNUV(I)-DPNUV(I)                                   RAD00670
          D(I)=0.0D0                                                   RAD00680
          WRITE (6,12)K,PQU(I),DPQU(I),NTYPE(I),ZERONU(I),PNUV(I),DPNUV(I),A RAD00690
         1(I),B(I),C(I),D(I),BDP(I),DDP(I),ZK(I)                       RAD00700
   12 FORMAT(I3,2X,A4,'-',A6,I5,3F10.2,2F10.5,2E10.2,F10.5,E10.2,F10.5) RAD00710
   15 CONTINUE                                                         RAD00720
C                                                                      RAD00730
C         READ BANDHEAD LOCATIONS                                      RAD00740
          READ(5,8825)(BDHD(I),I=1,ITOT)
 8825 FORMAT (8F9.3)                                                   RAD00750
          WRITE(6,8826)(BDHD(I),I=1,ITOT)                              RAD00760
 8826 FORMAT (26H0VALUES FOR BANDHEAD ARE  /(8F15.3))                  RAD00770
C                                                                      RAD00780
C         READ ACTIVE TRANSISION S FOR EACH 5 CM-1 INTERVAL            RAD00790
          DO 2002 I=1,INU
          READ (5,2001)NNT,(NT(I,J),J=1,NNT)                           RAD00800
          NTOT(I)=NNT                                                  RAD00810
 2001 FORMAT (24I3)                                                    RAD00820
 2002 CONTINUE                                                         RAD00830
C                                                                      RAD00840
C         READ N2 ABSORPTION COEFFICIENT IN UNITS OF ATM-2 METERS-1.   RAD00850
          READ(5,842) (ABSN2(I),I=1,INU)
  842 FORMAT(7E10.3)                                                   RAD00860
          WRITE(6,QABPR)                                               RAD00870
C         READ BENEDICT AND CALFEES WATER VAPOR DATA.                  RAD00880
          DO 522 I=1,IH2O
          READ(5,526) SNU(I),X(I),ALH2O(I),JP,KA,KC,JDP,KLA,KLC,EDP(I),XLL RAD00890
  526 FORMAT(F8.2,F10.4,F8.4,I4,2I3,I4,2I3,F9.2,F11.5)                 RAD00900
          WRITE(6,537) SNU(I),X(I),ALH2O(I),EDP(I)                     RAD00910
  537 FORMAT(1X,F8.2,F12.4,F9.4,F9.2)                                  RAD00920
  522 CONTINUE                                                         RAD00930
          READ (5,175)COS9                                             RAD00940
  175 FORMAT (F8.5)                                                    RAD00950
          WRITE (6,937)COS9                                            RAD00960
  937 FORMAT (8H0COS9 = F8.5)                                          RAD00970
C         READ CO2,N2O,AND CO LINE HALFWIDTHS.                         RAD00980
          READ(5,831) ALCO2,ALN2O,ALCO
  831 FORMAT(3F10.4)                                                   RAD00990
C         READ ABUNDANCES OF CO2,N2O,AND CO IN CM-ATM AND OF N2 IN FRACTION RAD01000
C         BY VOLUME9
          READ(5,811) ACO2,AN2O,ACO,AN2
  811 FORMAT(F11.3,3F7.3)                                              RAD01010
          WRITE(6,812) ACO2,AN2O,ACO,AN2                               RAD01020
  812 FORMAT(8H0ACO2 = F3.0,5X,7HAN2O = F5.3,2X,6HACO = F5.3,2X,6HAN2 = RAD01030
                                                                       RAD01040
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```
     1F5.3)                                                              RAD01050
      READ (5,940)DIF,LEVL                                               RAD01060
  940 FORMAT (F5.2,I3)                                                   RAD01070
C                                                                        RAD01080
C     ONE START OF NEXT CASE IF IINT GE NUMINT                           RAD01090
C                                                                        RAD01100
C     READ NUMBER OF ATMOSPHERIC LEVELS AND SECANT OF ZENITH ANGLE.
   45 READ (5,20)ITP,SEC                                                 RAD01110
   20 FORMAT (I3,F7.4)                                                   RAD01120
      WRITE (6,181)ITP,SEC                                               RAD01130
  181 FORMAT (7H0ITP = I3,6H SEC =F7.4)                                  RAD01140
C                                                                        RAD01150
C     CALL EXIT IF ITP LT NUMINT                                         RAD01160
C                                                                        RAD01170
      IF (ITP)46,46,43                                                   RAD01180
C                                                                        RAD01190
C     READ TEMPERATURE,PRESSURE,WATER VAPOR AMOUNT AND BROUND TEMPERATURE
   43 READ (5,13)(T(I),I=1,ITP)                                          RAD01200
   13 FORMAT (10F7.2)                                                    RAD01210
      READ (5,3)TG                                                       RAD01220
    3 FORMAT (F7.2)                                                      RAD01230
      WRITE (6,4)TG                                                      RAD01240
    4 FORMAT (6H TG = ,F7.2)                                             RAD01250
      READ (5,21)(P(I),I=1,ITP)                                          RAD01260
   21 FORMAT (8F9.6)                                                     RAD01270
      READ(5,23) (WAT(I),I=1,ITP)                                        RAD01280
   23 FORMAT(9E8.5)                                                      RAD01290
      READ (5,64)NUMINT                                                  RAD01300
   64 FORMAT (I3)                                                        RAD01310
      IINT=0                                                             RAD01320
C                                                                        RAD01330
C     OTHER START OF NEXT CASE  IF IINT  LT NUMINT                       RAD01340
C                                                                        RAD01350
   42 READ(5,22)BOTNU,TOPNU,DELTNU                                       RAD01360
   22 FORMAT(3F6.0)                                                      RAD01370
      WRITE(6,963) (BOTNU,TOPNU,DELTNU)                                  RAD01380
  963 FORMAT(1X,3F6.0)                                                   RAD01390
      DIFR = (BOTNU-2150.D0)/5.0D0&1.0D0                                 RAD01400
      JFNU=DIFR                                                          RAD01410
      KNU=JFNU&3                                                         RAD01420
      FNU=BOTNU                                                          RAD01430
   44 WRITE (6,999)FNU                                                   RAD01440
  999 FORMAT (5H1FNU=F6.0//)                                             RAD01450
      GBLAK=.0000119060 5D0*FNU**3.D0/(EXP(1.4388D0*FNU/TG)-1.D0)        RAD01460
      II=ITP-1                                                           RAD01470
   75 WRITE(6,542)(T(I),P(I),WAT(I),I=1,ITP)                             RAD01480
  542 FORMAT(3E16.8)                                                     RAD01490
      TRANS(ITP)=1.D0                                                    RAD01500
      NZP=NTOT(JFNU)                                                     RAD01510
C                                                                        RAD01520
C                                                                        RAD01530
C     START OF MAIN LOOP OVER VIBRATIONAL TRANSISION. INDEXING IS ARR.
C     SO THAT ONLY ACTIVE TRANSISIONS IN A PARTICULAR INTERVAL ARE
C     CONSIDERED
      DO 85 NTRANS=1,NZP                                                 RAD01540
      I=NT(JFNU,NTRANS)                                                  RAD01550
      IF (FNU&2.5D0-BOHD(I))550,50,50                                    RAD01560
  550 IF (ABS(FNU-ZERONU(I))-BND)54,50,50                                RAD01570
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```
   50 CONTINUE                                                          RAD0158
C                                                                       RAD0159
      DO 52 N=1,II                                                      RAD0160
      K=ITP-N                                                           RAD0161
      TRAN1(K,I)=1.0D0                                                  RAD0162
   52 CONTINUE                                                          RAD0163
C                                                                       RAD0164
      GO TO 85                                                          RAD0165
C                                                                       RAD0166
C     THE M VALUE (THE ROTATIONAL QUANTUM NUMBER) IS COMPUTED FOR THE
C     DESIRED FREQUENCY. THIS NUMBER WILL IN GENERAL BE NONINTEGRAL.
C
   54 LCOUNT(I)=1                                                       RAD0167
   55 SMO=(A(I)-SQRT(A(I)**2&4.0D0*B(I)*(FNU-ZERONU(I))))/(-2.D0*B(I))  RAD0168
   56 SM(I)=(FNU-ZERONU(I)-(((D(I)*SMO&C(I))*SMO&B(I))*SMO)*SMO)/A(I)   RAD0169
   57 IF (ABS(SM(I))-80.D0)557,50,50                                    RAD0170
  557 DELSM=ABS(SMO-SM(I))                                              RAD0171
      IF (DELSM-.01D0)60,58,58                                          RAD0172
   58 SMO=SM(I)                                                         RAD0173
      LCOUNT(I)=LCOUNT(I)&1                                             RAD0174
      IF (LCOUNT(I)-20)56,56,1001                                       RAD0175
 1001 WRITE (6,1003)I,DELSM                                             RAD0176
 1003 FORMAT (I3,E15.6,20H LCOUNT IS TOO LARGE)                         RAD0177
   60 CONTINUE                                                          RAD0178
C     THE MATRIX ELEMENT AND THE RELATIVE INTENSITY OF THE TRANSISION IS
C     NOW COMPUTED. THE ZK(I) ALSO INCLUDES ISOTOPIC ABUNDANCE.
C
      IF (NTYPE(I)-2)65,67,61                                           RAD0179
   61 IF (NTYPE(I)-4)69,71,73                                           RAD0180
   65 BIGA(I)=ABS(SM(I))                                                RAD0181
      IF (I-40)66,66,76                                                 RAD0182
   66 ZK1(I)=2.269D0*ZK(I)*300.D0/273.D0                                RAD0183
      GO TO 79                                                          RAD0184
   67 BIGA(I)=ABS((SM(I)&1.0D0)*(SM(I)-1.0D0)/SM(I))                    RAD0185
      GO TO 77                                                          RAD0186
   69 BIGA(I)=ABS((SM(I)&2.0D0)*(SM(I)-2.0D0)/SM(I))                    RAD0187
      GO TO 77                                                          RAD0188
   71 BIGA(I)=ABS((SM(I)&3.0D0)*(SM(I)-3.0D0)/SM(I))                    RAD0189
      GO TO 77                                                          RAD0190
   73 BIGA(I)=ABS((SM(I)&4.0D0)*(SM(I)-4.0D0)/SM(I))                    RAD0191
      GO TO 77                                                          RAD0192
   77 IF (I-40)78,78,76                                                 RAD01930
   76 ZK1(I)=0.7667D0*ZK(I)*300.0D0/273.0D0                             RAD01940
      GO TO 79                                                          RAD01950
   78 ZK1(I)=1.1345D0*ZK(I)*300.D0/273.D0                               RAD01960
C     BIGD(I) IS THE LINE SPACING.
   79 BIGD(I)=((4.D0*D(I)*SM(I)&3.D0*C(I))*SM(I)&2.0D0*B(I))*SM(I)&A(I) RAD01970
      IF (I-40)887,887,889                                              RAD01980
  887 IF (NTYPE(I)-1)888,888,889                                        RAD01990
  888 BIGD(I)=2.0D0*BIGD(I)                                             RAD02000
  889 CONTINUE                                                          RAD02010
      DPNUR(I)=((SM(I)*SM(I))-SM(I))*BDP(I)&((SM(I)*SM(I))-SM(I))*((SM(IRAD02020
     1)*SM(I))-SM(I))*DDP(I)                                            RAD02030
      DPNU(I)=DPNUV(I)&DPNUR(I)                                         RAD02040
      SSM=0.D0                                                          RAD02050
      SSGM=0.D0                                                         RAD02060
```

```
C                                                                       RAD02070
C     MAJOR LOOP OVER ATMOSPHERIC LEVEL. INDEXING IS REVERSED SO THAT
C     SUMS IN THIS LOOP WILL START AT THE TOP OF THE ATMOSPHERE AND WORK
C     DOWNWARD. THE SUMS (SSM AND SSGM) IN THIS LOOP ARE RELATED TO THE
C     APPLICATION OF THE CURTIS-GODSON APPROXIMATION.
C     NOTE THAT THE K INDEX USUALLY RUNS FROM THE BOTTOM OF THE
C     ATMOSPHERE TO THE TOP.
      DO 39 N=1,II                                                      RAD02080
      K=ITP-N                                                           RAD02090
      TS=(T(K)&T(K&1))/2.D0                                             RAD02100
      IF (I-40)311,311,312                                              RAD02110
  311 ABC=1.D0-EXP(-959.68D0/TS)                                        RAD02120
      GO TO 313                                                         RAD02130
  312 IF(I-93) 314,314,315                                              RAD02140
  314 ABC = 1.0D0-EXP(-847.12D0/TS)                                     RAD02150
      GO TO 313                                                         RAD02160
  315 ABC = 1.0D0                                                       RAD02170
  313 QV=1.D0/(ABC*ABC)                                                 RAD02180
      S=(ZK1(I)/QV)*(1.4388D0/TS)*BIGA(I)*BDP(I)*ENU*EXP((-1.4388D0/TS)*RAD02190
     XDPNU                                                              RAD02200
     1(I))*(1.D0-EXP((-1.4388D0/TS)*ENU))                               RAD02210
      PA=(P(K)&P(K&1))/2.D0                                             RAD02220
      DELP=P(K)-P(K&1)                                                  RAD02230
      IF (I-40)111,111,112                                              RAD02240
  111 DMDP=ACO2*SEC                                                     RAD02250
      ALPHA =ALCO2                                                      RAD02260
      GO TO 113                                                         RAD02270
  112 IF(I-93) 116,116,117                                              RAD02280
  116 DMDP = AN2O*SEC                                                   RAD02290
      ALPHA = ALN2O                                                     RAD02300
      GO TO 113                                                         RAD02310
  117 DMDP = ACO*SEC                                                    RAD02320
      ALPHA = ALCO                                                      RAD02330
  113 IF(DMDP.EQ.0.0D0) GO TO 173                                       RAD02340
      SGDM=S*ALPHA*PA*(17.2629D0/SQRT(TS))*DMDP*DELP                    RAD02350
      SDM=S*DMDP*DELP                                                   RAD02360
  114 SSM=SSM&SDM                                                       RAD02370
      SSGM=SSGM&SGDM                                                    RAD02380
      ARG1=6.283185D0*SSGM/(BIGD(I)*SSM)                                RAD02390
      ARG2=SSM/(COS9*BIGD(I))                                           RAD02400
  171 IF(ARG2-1.0D-4) 173,173,102                                       RAD02410
  173 TRAN1(K,I) = 1.0D0                                                RAD02420
      GO TO 39                                                          RAD02430
C                                                                       RAD02440
C     TISR DOES GENERAL ELSASSER BAND COMPUTATION OF TRANSMISSION.
  102 CALL TISR(ARG1,ARG2,TRAN,DUM1,DUM2,DUM3)                          RAD02450
      TRAN1(K,I)=TRAN                                                   RAD02460
   39 CONTINUE                                                          RAD02470
C                                                                       RAD02480
   85 CONTINUE                                                          RAD02490
C                                                                       RAD02500
C                                                                       RAD02510
C                                                                       RAD02520
      DO 33 K 1,IT[illegible]                                           RAD02530
      TRANS(K)=[illegible]                                              RAD02540
      EXPNT(K) = 0.D0                                                   RAD02550
   33 CONTINUE                                                          RAD02560
C     BETWEEN THIS POINT AND STATEMENT 35, WE COMPUTE TRANSMISSION DUE
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```
C       TO BOTH N2 AND H2O. AS THE WATER LINES ARE ASSUMED TO BE RANDOM
C       AND THE NITROGEN ABSORPTION COEF. IS SLOWLY VARYING, WE CAN
C       COMPUTE THE ABSORPTION DUE TO EACH OF THESE MOLECULES SEPARATELY
C       AND MULTIPLY THE RESULTS. THE WATER SUBROUTINE COMPUTES THE WATER
C       VAPOR ABSORPTION BY MEANS OF THE STATISTICAL MODEL AND ACTUAL
C       LINE PARAMETERS.
        IF(WAT(1).GT.0.0D0) CALL WATER(ITP,IH2O,FNU,DELTNU,TRH2O)       RAD0257
C                                                                       RAD0258
        DO 35 N=1,II                                                    RAD0259
        K=ITP-N                                                         RAD0260
C                                                                       RAD0261
        DO 36 NTRANS=1,NZP                                              RAD0262
        I=NT(JFNU,NTRANS)                                               RAD0263
        IF(TRANS(K).LT.1.0D-20) TRANS(K) = 0.0D0                        RAD0264
        TRANS(K)=TRANS(K)*TRAN1(K,I)                                    RAD0265
   36 CONTINUE                                                          RAD0266
C                                                                       RAD0267
C       COMPUTE TRANSMISSION DUETO NITROGEN                             RAD0268
        TS = (T(K)&T(K&1))/2.D0                                         RAD0269
        PA = (P(K)&P(K&1))/2.0D0                                        RAD0270
        DELP = (P(K)-P(K&1))                                            RAD0271
        SCHT = 2.926D1*TS                                               RAD0272
        EXPNT(K) = EXPNT(K&1)&AN2*PA*SCHT*DELP*ABSN2(JFNU)              RAD0273
        TRN2 = EXP(-EXPNT(K))                                           RAD0274
        TRANS(K) = TRANS(K)*TRN2                                        RAD0275
        IF(WAT(1).GT.0.0D0) TRANS(K) = TRANS(K)*TRH2O(K)                RAD0276
C       COMPUTE TRANSMISSION DUETO NITROGEN                             RAD0277
   35 CONTINUE                                                          RAD0278
C                                                                       RAD0279
        MM=ITP-1                                                        RAD0280
        WRITE (6,543)(TRANS(K),K=1,MM)                                  RAD0281
  543 FORMAT (6E15.8)                                                   RAD0282
C                                                                       RAD0283
        DO 31 K=1,ITP                                                   RAD0284
        BLAK(JFNU,K)=.00001190605D0*FNU**3.D0/(EXP(1.4388D0*FNU/T(K))-1.D0RAD0285
       X)                                                               RAD0286
        PRES(K)=P(K)*1013.D0                                            RAD0287
   31 CONTINUE                                                          RAD0288
C                                                                       RAD0289
        WRITE (6,603)(BLAK(JFNU,K),K=1,ITP)                             RAD0290
  603 FORMAT (8E15.8)                                                   RAD0291
        DFLUX=0.D0                                                      RAD0292
C                                                                       RAD0293
C       IN THE FOLLOWING LOOP (TO STATEMENT 34) THE GROUNDWORK IS LAID FOR
C       COMPUTING INTEGRAL BDTAU. THIS IS DONE BOTH BY SIMPSONS RULE AND
C       THE TRAPEZOIDAL RULE. IF THE TAU SPACING IS LARGE (I.E. GT DIF),
C       THE TEMPERATURE IS ASSUMED TO DEPEND ON PRESSURE LOGARITHMICALLY.
C       IN THAT CASE THE TAU SPACING IS DIVIDED BY LEVEL.
        DO 34 K=1,MM                                                    RAD02940
        DTAU(K)=TRANS(K&1)-TRANS(K)                                     RAD02950
        IF(P(K&1).EQ.0.0D0) P(K&1)=1.0D-10                              RAD02960
        IF(PRES(K&1).EQ.0.0D0) PRES(K&1)=1.0D0-10                       RAD02970
  430 APRES(K)=DLOG10(PRES(K))-DLOG10(PRES(K&1))                        RAD02980
        FBLAK(K)=(BLAK(JFNU,K)&BLAK(JFNU,K&1))/2.D0                     RAD02990
        DTDP(K)=DTAU(K)/APRES(K)                                        RAD03000
        DTDPB(K)=DTDP(K)*FBLAK(K)                                       RAD03010
```

```
      TAUBAR=(TRANS(K)&TRANS(K&1))/2.D0                                 RAD03020
      IF (DTAU(K)-DIF)941,942,942                                       RAD03030
  941 TS=(T(K)&T(K&1))/2.D0                                             RAD03040
      ABLAK=.00001190605D0*FNU**3.D0/(EXP(1.4388D0*FNU/TS)-1.D0)        RAD03050
      GO TO 948                                                         RAD03060
  942 IF (P(K&1))941,941,933                                            RAD03070
  933 IF (T(K)-T(K&1))931,941,931                                       RAD03080
  931 CON=(-DLOG(P(K&1)/P(K)))/(T(K&1)-T(K))                            RAD03090
      VEL=LEVL                                                          RAD03100
      DTRAN=DTAU(K)/VEL                                                 RAD03110
      DPRES=(P(K)-P(K&1))/VEL                                           RAD03120
      CBLAK=BLAK(JFNU,K)                                                RAD03130
      ASIMP(K)=0.D0                                                     RAD03140
      GTRAN=TRANS(K)&DTRAN                                              RAD03150
      PO=P(K)                                                           RAD03160
      J=1                                                               RAD03170
  946 R=PO-DPRES                                                        RAD03180
      TS=(-DLOG(R/P(K)))/CON&T(K)                                       RAD03190
      BBLAK=.00001190605D0*FNU**3.D0/(EXP(1.4388D0*FNU/TS)-1.D0)        RAD03200
      BSIMP=DTRAN*(CBLAK&BBLAK)/2.D0                                    RAD03210
      J=J&1                                                             RAD03220
      PO=R                                                              RAD03230
      ASIMP(K)=ASIMP(K)&BSIMP                                           RAD03240
      CBLAK=BBLAK                                                       RAD03250
      GTRAN=GTRAN&DTRAN                                                 RAD03260
      IF (J-LEVL)946,946,945                                            RAD03270
  948 ASIMP(K)=(DTAU(K)/6.D0)*(BLAK(JFNU,K)&BLAK(JFNU,K&1)&4.D0*ABLAK)  RAD03280
  945 ATRAP(K)=DTAU(K)*(BLAK(JFNU,K)&BLAK(JFNU,K&1))/2.D0               RAD03290
   34 CONTINUE                                                          RAD03300
C                                                                       RAD03310
      DTDPO = DTDP(1)                                                   RAD03311
      DTDPBO = DTDPB(1)                                                 R1403312
      DO 345 K = 1,MM                                                   R1403313
      IF(DTDP(K).GT.DTDPO) DTDPO=DTDP(K)                                R1403314
      IF(DTDPB(K).GT.DTDPBO) DTDPBO=DTDPB(K)                            R1403315
  345 CONTINUE                                                          RAD03316
      DO 347 K=1,MM                                                     RAD03317
      DTDP(K)=DTDP(K)/DTDPO                                             RAD03318
      DTDPB(K)=DTDPB(K)/DTDPBO                                          RAD03319
  347 CONTINUE                                                          RAD0331X
C     AVOID DIVISION BY ZERO                                            RAD03320
C                                                                       RAD03330
      DO 648 K=1,ITP                                                    RAD03340
      IF (ASIMP(K)-1.D-10)647,647,648                                   RAD03350
  647 ASIMP(K)=1.0D0                                                    RAD03360
      ATRAP(K)=1.0D0                                                    RAD03370
  648 CONTINUE                                                          RAD03380
C                                                                       RAD03390
C     WEIGHTING FUNCTIONS (TW) ARE COMPUTED IN SUCH A WAY THAT THE
C     SIMPSONS RULE INTEGRATION IS ACHIEVED BY A SUMMATION OF B TIMES W.
      DO 38 K=1,ITP                                                     RAD03400
      IF (K-1)46,93,92                                                  RAD03410
   92 IF (K-ITP)95,94,46                                                RAD03420
   93 TW(1)=DTAU(K)*ASIMP(K)/(2.D0*ATRAP(K))                            RAD03430
      GO TO 37                                                          RAD03440
   94 TW(K)=DTAU(K-1)*ASIMP(K-1)/(2.D0*ATRAP(K-1))                      RAD03450
      GO TO 37                                                          RAD03460
   95 TW(K)=(DTAU(K-1)*ASIMP(K-1)/ATRAP(K-1)&DTAU(K)*ASIMP(K)/ATRAP(K))/RAD03470
```

```
      12.D0                                                             RAD0348
   37 DFLUX=DFLUX&BLAK(JFNU,K)*TW(K)                                    RAD0349
   38 CONTINUE                                                          RAD0350
C                                                                       RAD0351
      TW(1)=TW(1)&TRANS(1)                                              RAD0352
C                                                                       RAD0353
      DO 2011 K=1,ITP                                                   RAD0354
      AWT(JFNU,K)=TW(K)                                                 RAD0355
 2011 CONTINUE                                                          RAD0356
C                                                                       RAD0357
      WRITE (6,98)(K,TW(K),K=1,ITP)                                     RAD0358
   98 FORMAT (5(4H WT(,I2,4H) = E14.7))                                 RAD0359
      TFLUX=(DFLUX&GBLAK*TRANS(1))                                      RAD0360
      MJ=ITP-1                                                          RAD0361
      WRITE (6,7775)                                                    RAD0362
 7775 FORMAT (40X,7H DT/DLP)                                            RAD0363
      WRITE (6,1)(DTDP(K),K=1,MJ)                                       RAD0364
    1 FORMAT (6E15.8)                                                   RAD0365
      WRITE (6,7776)                                                    RAD0366
 7776 FORMAT (40X,11H (DT/DLP)*B)                                       RAD0367
      WRITE (6,1)(DTDPB(K),K=1,MJ)                                      RAD0368
      WRITE (6,28)FNU,TFLUX                                             RAD0369
   28 FORMAT (7H FNU = F6.0,9H TFLUX = E16.8)                           RAD0370
      TINT(JFNU)=TFLUX                                                  RAD0371
   29 FNU=FNU&5.0D0                                                     RAD0372
      JFNU=JFNU&1                                                       RAD0373
      IF (FNU-TOPNU)44,44,602                                           RAD0374
  602 DIFR=(TOPNU-BOTNU)/5.D0&1.0D0                                     RAD0375
      KKNU=DIFR-3.D0                                                    RAD0376
C                                                                       RAD0377
C                                                                       RAD0378
C     IN THE FOLLOWING LOOP (TO 621) A TRIANGULAR SLIT FUNCTION IS
C     CONVOLVED WITH THE FLUX DISTRIBUTION. THE WEIGHTS (AVWAT) ARE
C     ADJUSTED TO GIVE THE CORRECT SMOOTHED FLUX (AINT OR FCP315).
      DO 621 I=KNU,KKNU                                                 RAD0379
      DEX=I                                                             RAD0380
      GNU = 5.D0*(DEX-1.D0)&2150.D0                                     RAD0381
      FCP015=(4.D0*TINT(I)&3.D0*(TINT(I-1)&TINT(I&1))&2.D0*(TINT(I-2)&TIRAD0382
     XNT(I&2                                                            RAD0383
     1))&TINT(I-3)&TINT(I&3))/16.D0                                     RAD0384
      BINT=0.D0                                                         RAD0385
C                                                                       RAD0386
      DO 622 K=1,ITP                                                    RAD0387
      AVWAT(I,K)=(4.D0*AWT(I,K)&3.D0*(AWT(I-1,K)&AWT(I&1,K))&2.D0*(AWT(IRAD0388
     X-2,K)&                                                            RAD0389
     1AWT(I&2,K))&AWT(I-3,K)&AWT(I&3,K))/16.D0                          RAD0390
      BINT=BINT&AVWAT(I,K)*BLAK(I,K)                                    RAD0391
  622 CONTINUE                                                          RAD0392
C                                                                       RAD0393
      DO 623 K=1,ITP                                                    RAD0394
      AVWAT(I,K)=(FCP015/BINT)*AVWAT(I,K)                               RAD0395
  623 CONTINUE                                                          RAD0396
C                                                                       RAD0397
      WRITE (6,625)GNU,FCP015,BINT                                      RAD0398
  625 FORMAT (7H0FNU = F6.0,7H AINT =E15.7,8H BINT = E15.7///)          RAD0399
      WRITE (6,627)(I,K,AVWAT(I,K),K=1,ITP)                             RAD0400
```

```
  627 FORMAT (4(5H AWT(,I2,1H,I2,4H) = E14.7))                      RAD04010
      WRITE (6,628)(I,K,BLAK(I,K),K=1,ITP)                          RAD04020
  628 FORMAT (4(6H BLAK(,I2,1H,,I2,4H) = E14.7))                    RAD04030
  621 CONTINUE                                                      RAD04040
C                                                                   RAD04050
C                                                                   RAD04060
      IINT=IINT&1                                                   RAD04070
      IF (IINT-NUMINT)42,45,45                                      RAD04080
   46 STOP                                                          RAD04090
      END                                                           RAD04100
                                                                    WAT00010
```

C. Water Vapor Program Listing

```
      IMPLICIT REAL*8 (A-H,O-Z)
      SUBROUTINE WATER (ITP,IH2O,FNU,DELTNU,TRH2O)

      L8052 MCCLATCHEY R4132300000
      WATER VAPOR TRANS

   N IS THE TOTAL NUMBER OF LINES

      DIMENSION EM(40),EMP(40),EP(40),EQWTH(40),TRH2O(40)
      COMMON/H2O/SNU(450),S(450),ALPHA(450),EDP(450),P(40),T(40),WAT(40)


      START OF DELTNU INTERVAL

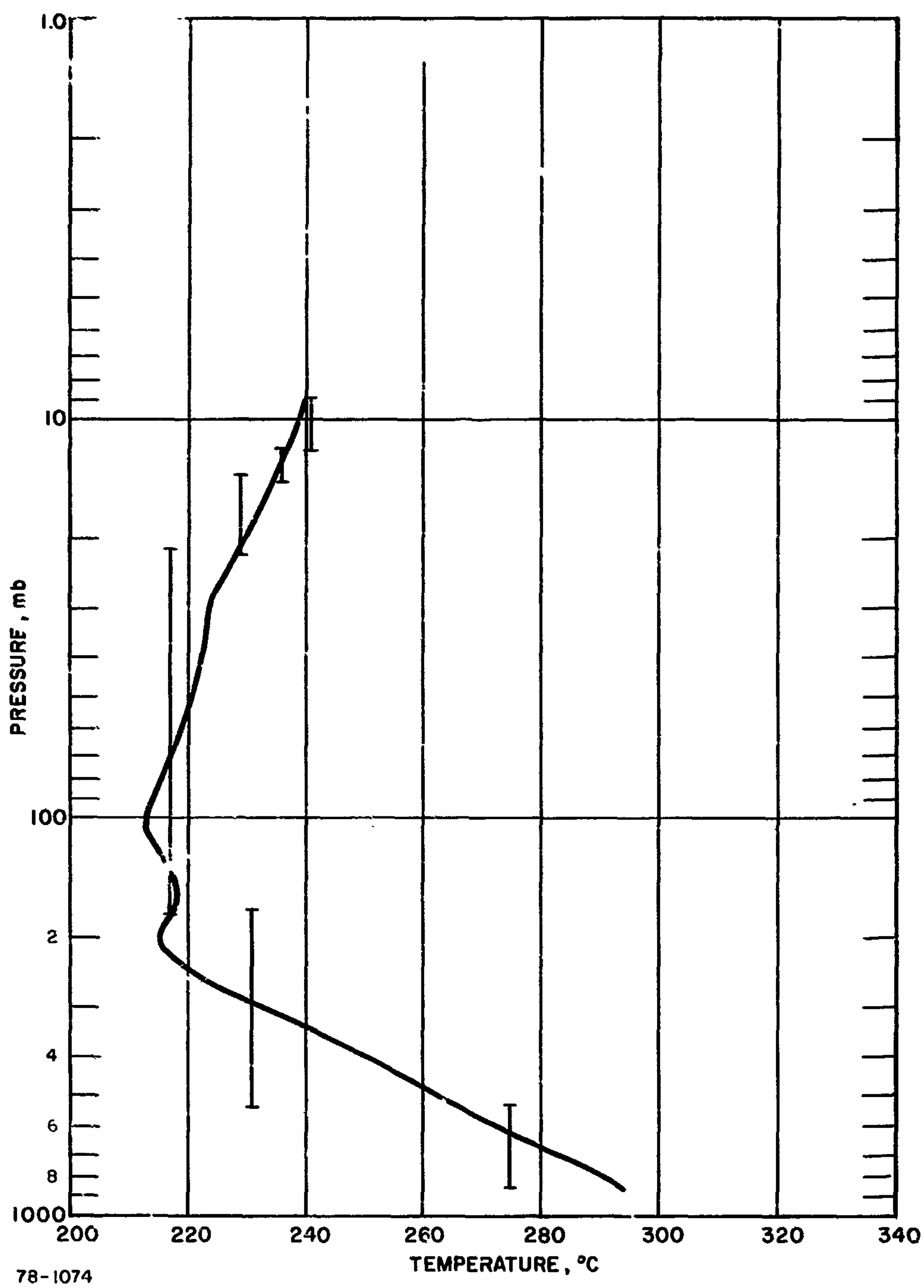

  100 DO 40 I=1,IH2O
      IF(SNU(I).GE.FNU) GO TO 45
   40 CONTINUE

   45 NUBOT = I
      TNU = FNU&DELTNU

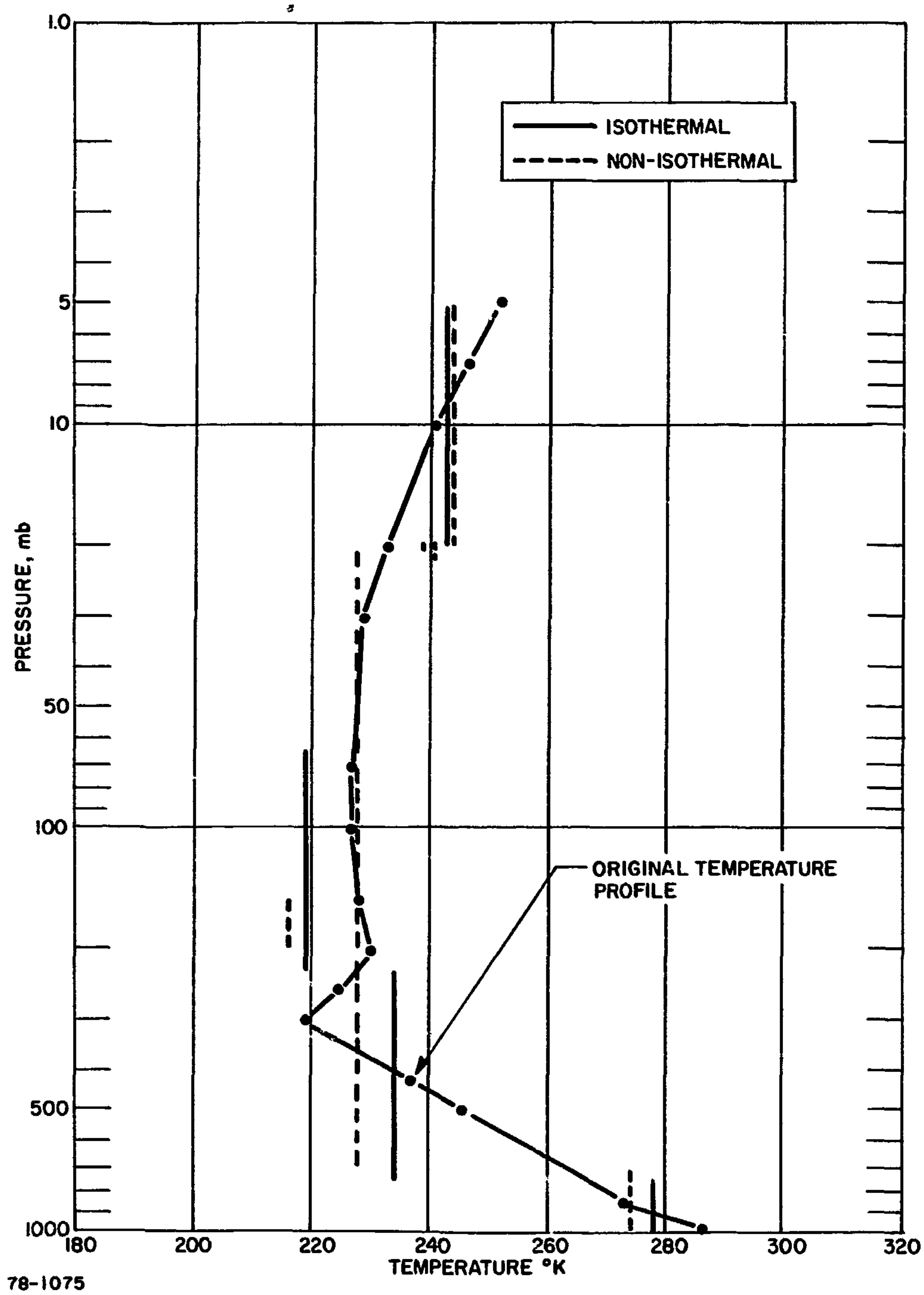
      DO 50 I=NUBOT,IH2O
      IF(SNU(I).GT.TNU) GO TO 55
   50 CONTINUE

   55 NUTOP = I-1
      SSUMO = 0.D0
      SASUMO = 0.D0
C
      DO 60 I=NUBOT, NUTOP
      SSUMO = S(I)&SSUMO
   60 SASUMO = SQRT(S(I)*ALPHA(I))&SASUMO
C
      KK=ITP-1
      DO 61 K =1,ITP
      EM(K) = 0.D0
      EMP(K) = 0.D0
   61 EP(K) = 0.D0
      SSUM = 0.D0
      SASUM = 0.D0
      BARNU = FNU&(DELTNU/2.0D0)
C
C
      DO 70 N=1,KK
      K = ITP-N
      KP1=K&1
      TBAR = (T(K)&T(KP1))/2.D0
```

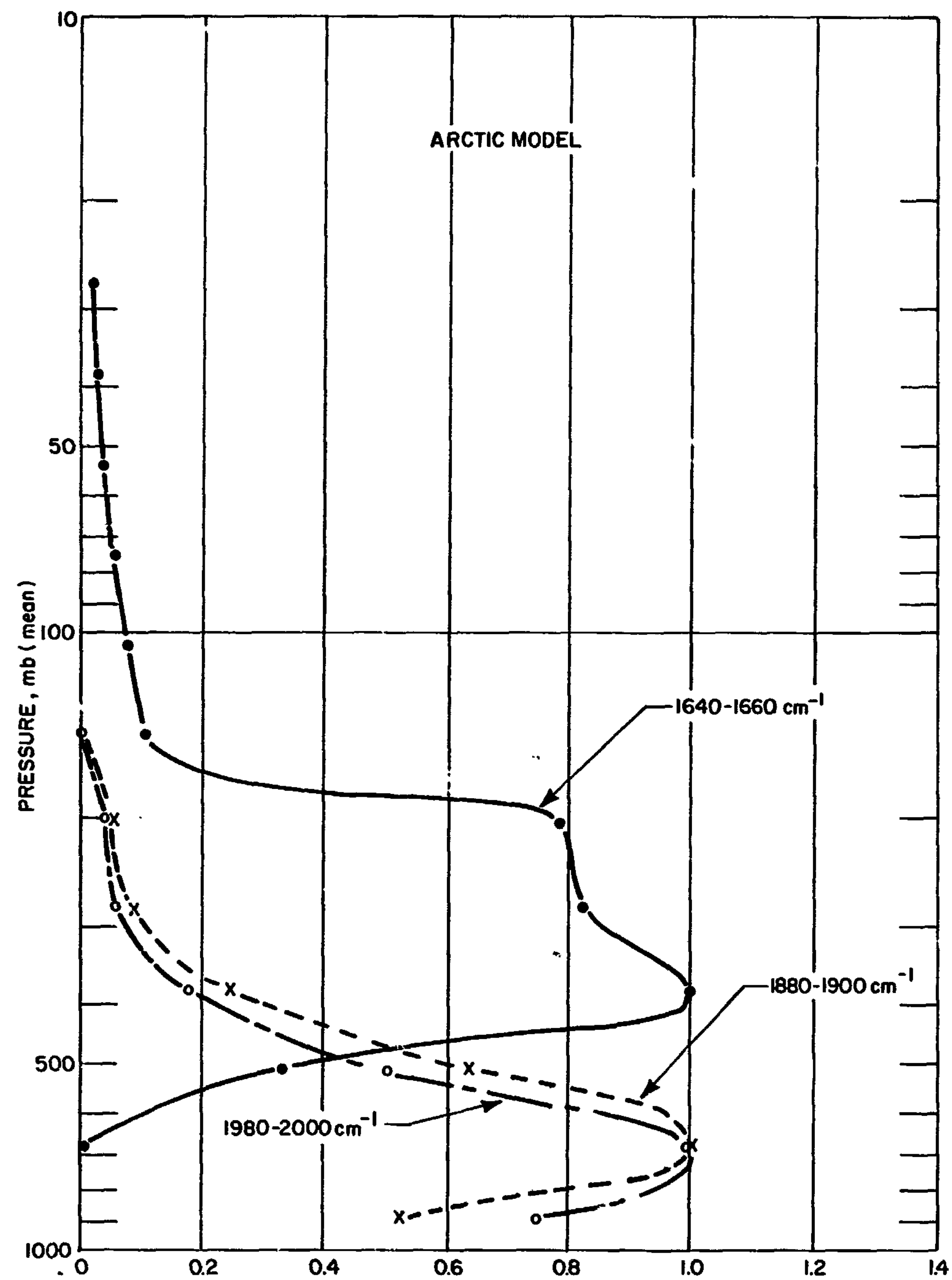
```
      TBAR1 = 4.88003/(TBAR**1.5)                                      WAT00490
      TBAR2=1.0D0/TBAR - 1.0D0/2.877D2                                 WAT00500
      PA = (P(K)&P(KP1))/2.0D0                                         WAT00510
C                                                                      WAT00520
      DO 80 I=NUBOT,NUTOP                                              WAT00530
      SLINE = (S(I)*TBAR1)*EXP(-1.439*EDP(I)*TBAR2)                    WAT00540
      SSUM = SSUM&SLINE                                                WAT00550
   80 SASUM = SASUM & SQRT(SLINE*ALPHA(I)*PA)                          WAT00560
C                                                                      WAT00570
      X=SSUM/SSUMO                                                     WAT00580
      Y = (SASUM/SASUMO)**2.D0                                         WAT00590
      DELTM = WAT(K)-WAT(KP1)                                          WAT00600
      IF(DELTM.LT.1.0D-10) GO TO 170                                   WAT00610
      EM(K) = X*DELTM&EM(KP1)                                          WAT00620
      EMP(K) = Y*PA*DELTM & EMP(KP1)                                   WAT00630
C                                                                      WAT00640
C                                                                      WAT00650
      EP(K)=EMP(K)/EM(K)                                               WAT00660
      GO TO 70                                                         WAT00670
  170 EM(K)=0.0D0                                                      WAT00680
      EP(K)=1.0D-10                                                    WAT00690
   70 CONTINUE                                                         WAT00700
C                                                                      WAT00710
C                                                                      WAT00720
      DO 71 K=1,FK                                                     WAT00730
      KM1 = K-1                                                        WAT00740
      KP1=K&1                                                          WAT00750
      EQWTHK=0.0D0                                                     WAT00760
      XEMK = EM(K)                                                     WAT00770
      XEPK = EP(K)                                                     WAT00780
C                                                                      WAT00790
      DO 90 I=NUBOT,NUTOP                                              WAT00800
      U = S(I)*XEMK /(6.2832D0*ALPHA(I)*XEPK )                         WAT00810
      CALL LRF(U)                                                      WAT00820
   90 EQWTHK    = 6.2832D0*ALPHA(I)*XEPK *U&EQWTHK                     WAT00830
C                                                                      WAT00840
      EQWTH(K) = EQWTHK                                                WAT00850
   71 TRH2O(K)=EXP(-EQWTH(K)/DELTNU)                                   WAT00860
  110 RETURN                                                           WAT00870
      END                                                              WAT00880
        IMPLICIT REAL*8 (A-H,O-Z)                                      TIS00010
      SUBROUTINE TISR(ARG1,ARG2,TRANS,DUM1,DUM2,DUM3)                  TIS00020
C     LAST 3 ARGS DO NOTHING.                                          TIS00030
      DIMENSION C(7),COUNT(14)                                         TIS00040
      DATA NZERO,ABC3/0,0.0D0/                                         TIS00050
      DATA TWOPI/ 6.2831853D0/                                         TIS00060
      IF(NZERO.NE.0)  GO TO 100                                        TIS00070
99    DO 98 I=1,14                                                     TIS00080
98    COUNT(I)=I                                                       TIS00090
      C(1)=.5D0                                                        TIS00100
      C(2)=3.D0/8.D0                                                   TIS00110
      C(3)=5.D0/16.D0                                                  TIS00120
      C(4)=35.D0/128.D0                                                TIS00130
      C(5)=63.D0/256.D0                                                TIS00140
      C(6)=231.D0/1024.D0                                              TIS00150
      C(7)=429.D0/2048.D0                                              TIS00160
```

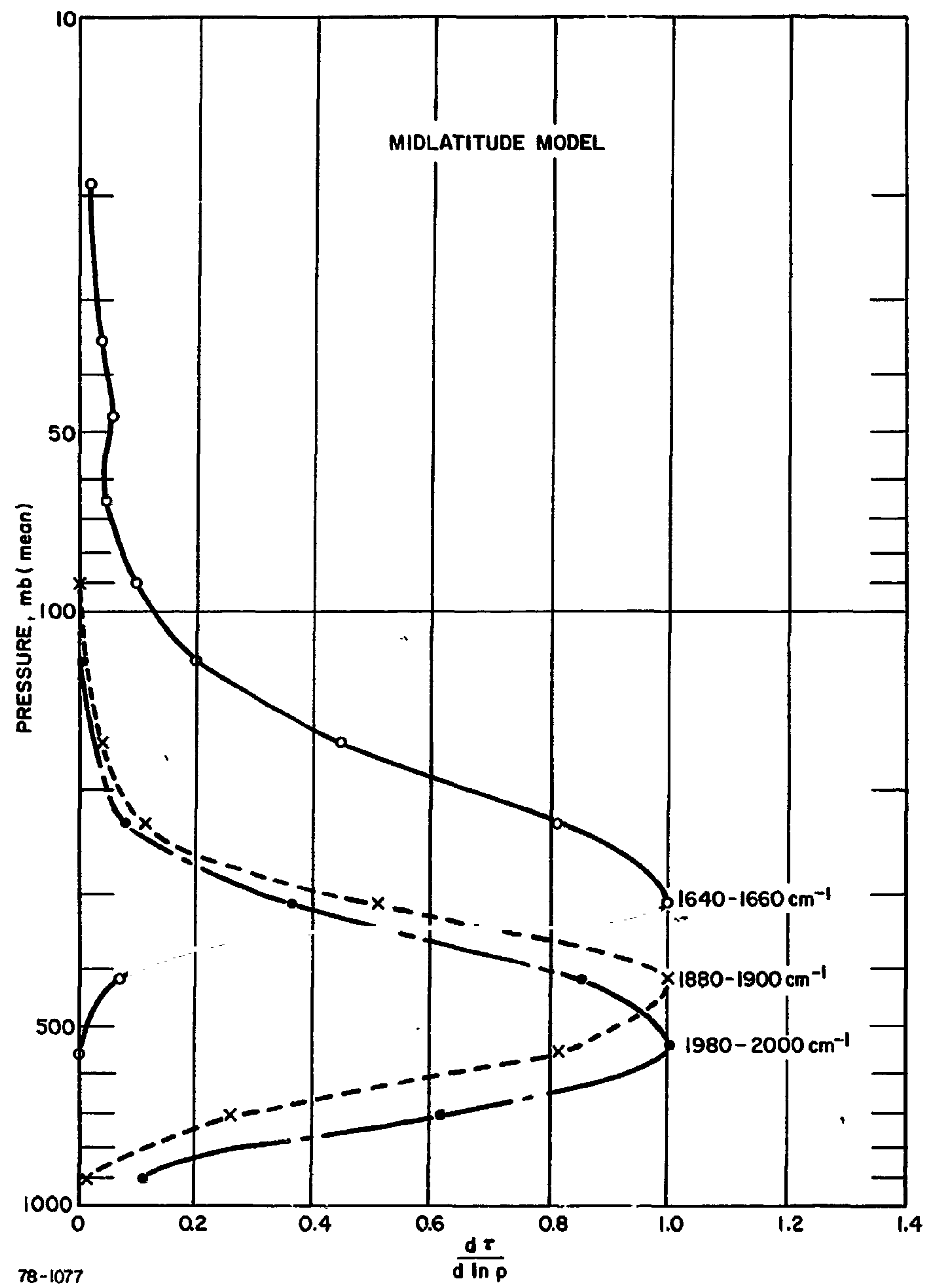


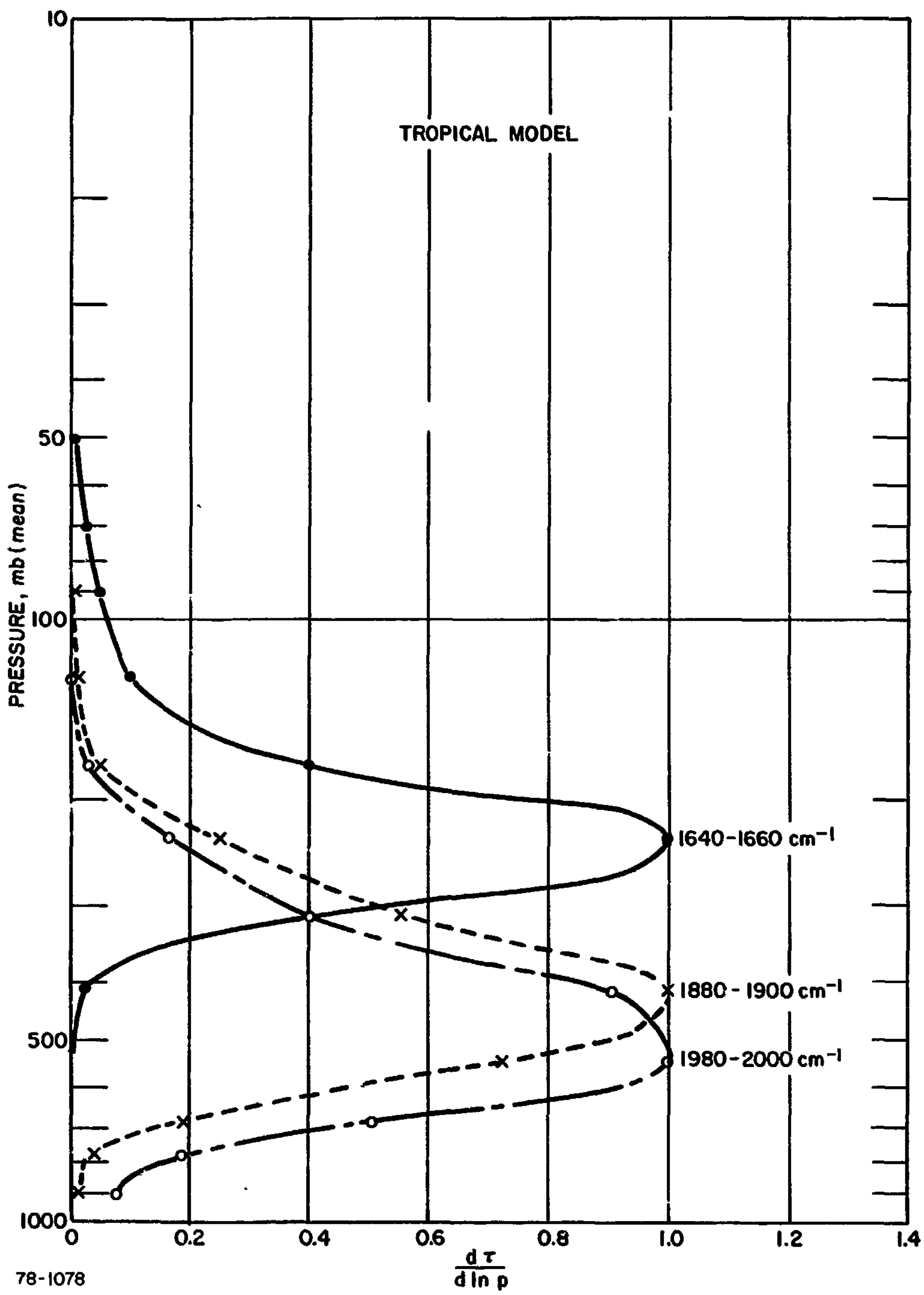
PRESSURE, mb
1.0
10
100
2
4
6
8
1000
200
220
240
260
280
300
320
340
TEMPERATURE, °C
78-1074

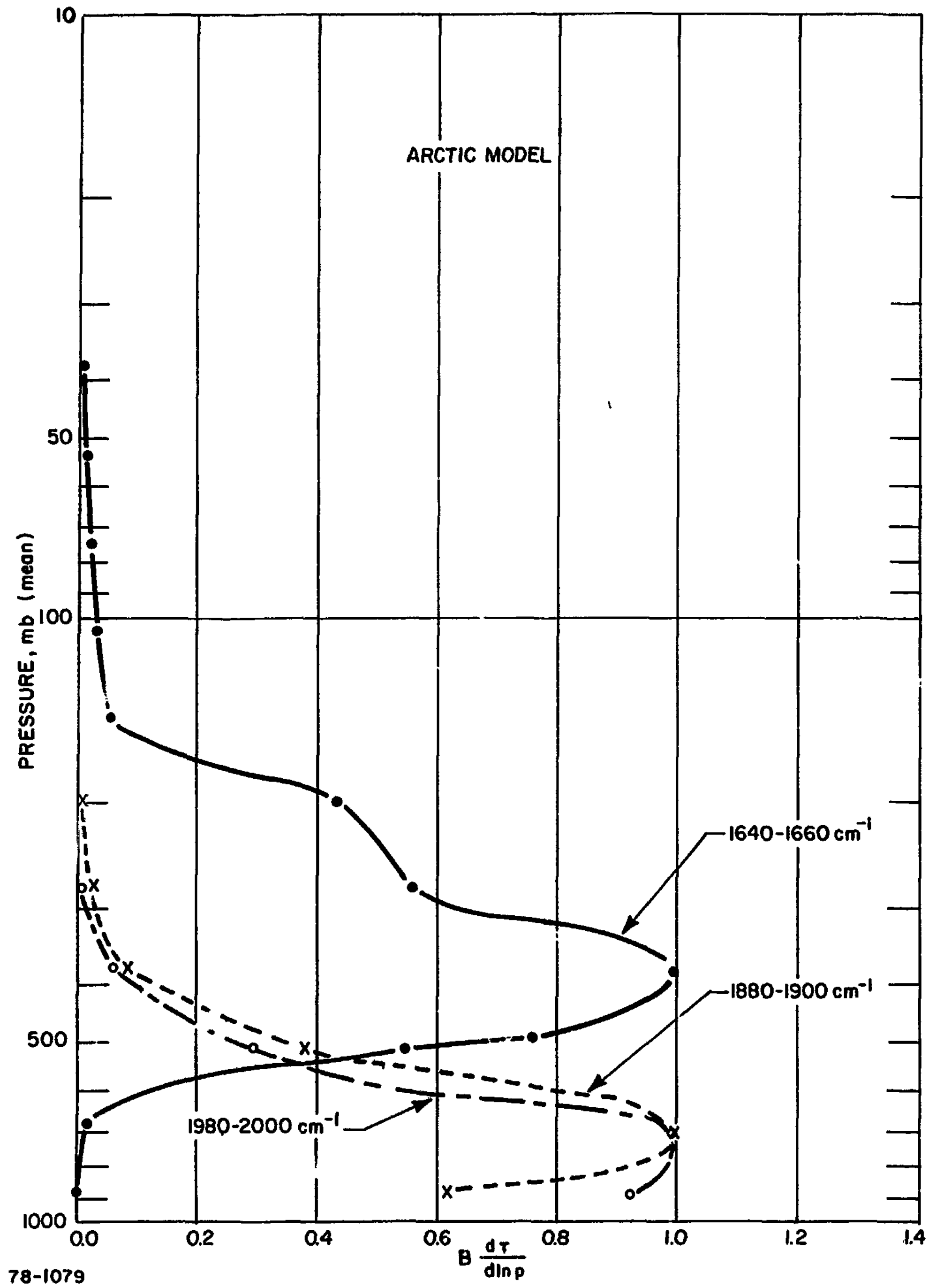


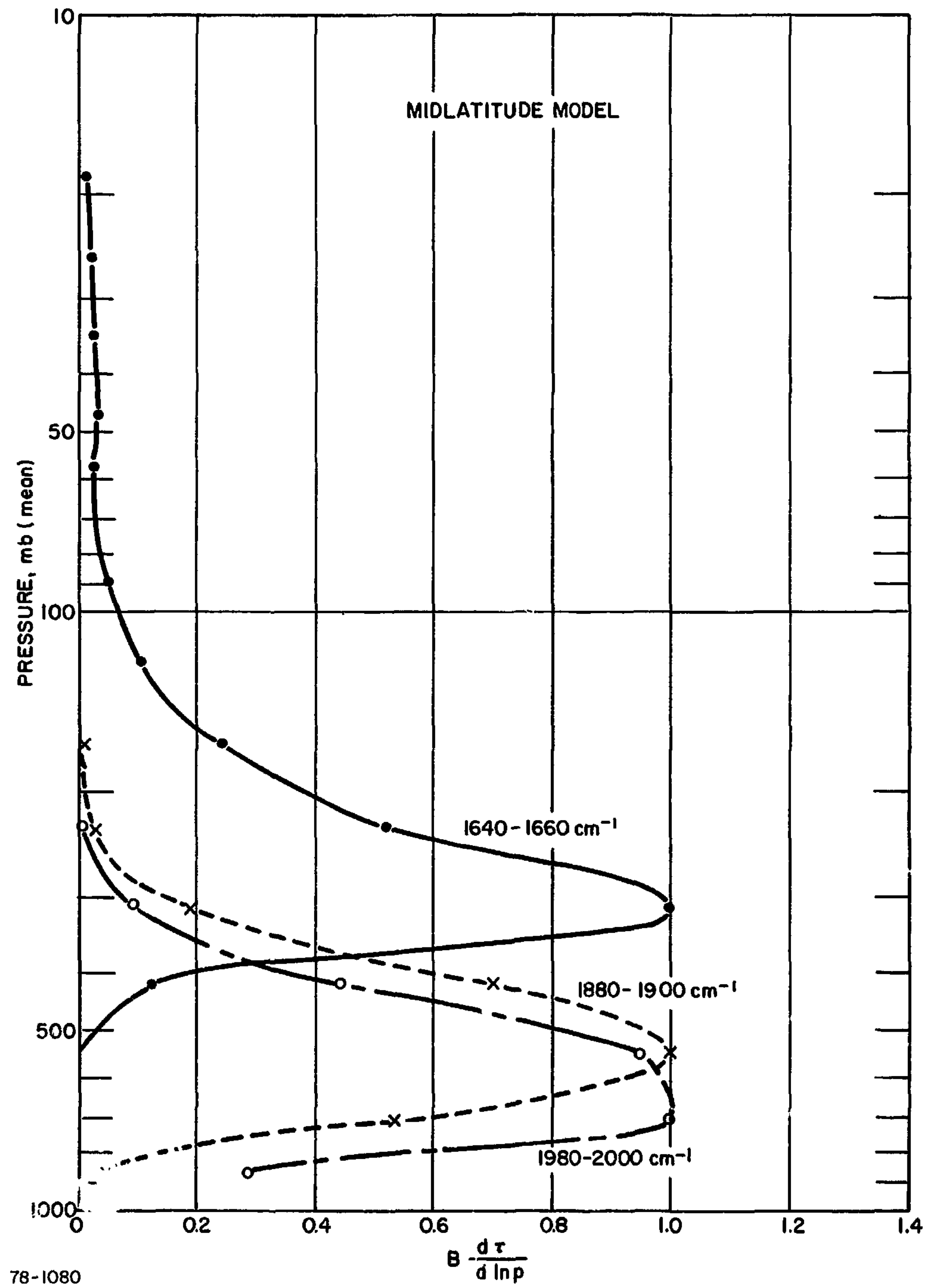
ISOTHERMAL
NON-ISOTHERMAL
ORIGINAL TEMPERATURE PROFILE
PRESSURE, mb
1.0
5
10
50
100
500
1000
180
200
220
240
260
280
300
320
TEMPERATURE °K
78-1075


ARCTIC MODEL
1640-1660 cm^{-1}
1880-1900 cm^{-1}
1980-2000 cm^{-1}
PRESSURE, mb (mean)
10
50
100
500
1000
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$d\tau/d\ln p$
78-1076

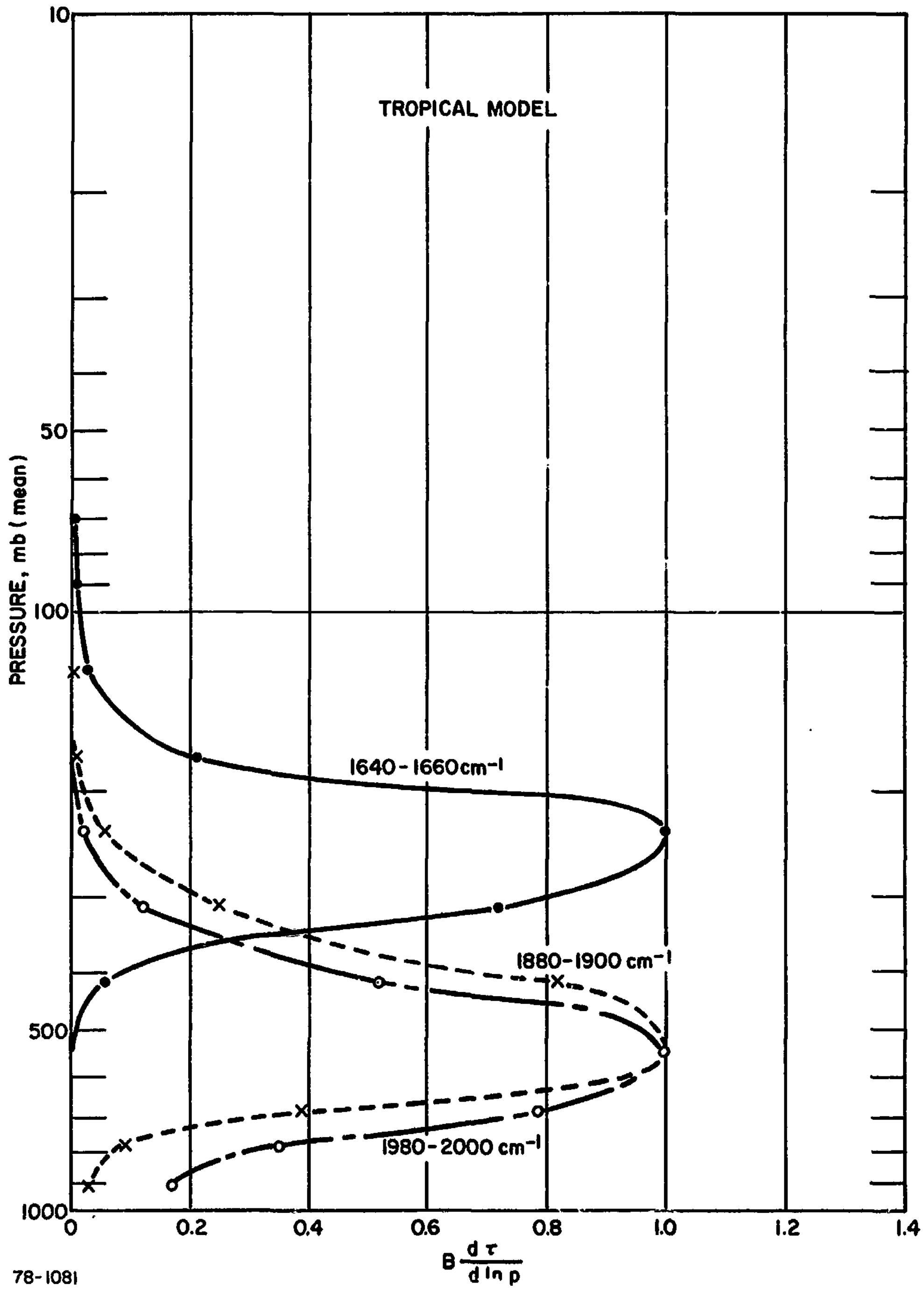

MIDLATITUDE MODEL
PRESSURE, mb (mean)
10
50
100
500
1000
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
d τ / d ln p
1640-1660 cm⁻¹
1880-1900 cm⁻¹
1980-2000 cm⁻¹
78-1077

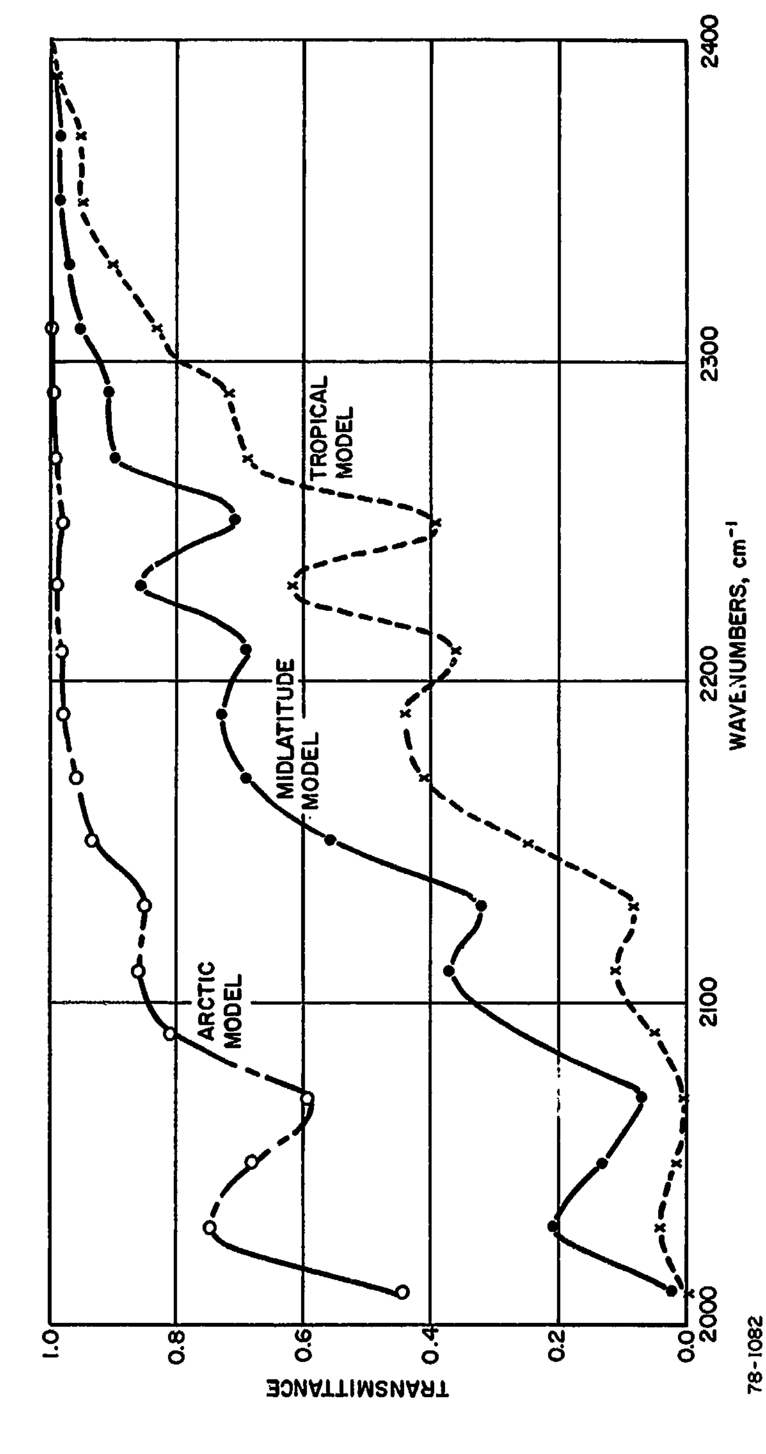

TROPICAL MODEL
PRESSURE, mb (mean)
10
50
100
500
1000
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$\frac{d\tau}{d \ln p}$
1640-1660 cm^{-1}
1880 - 1900 cm^{-1}
1980-2000 cm^{-1}
78-1078

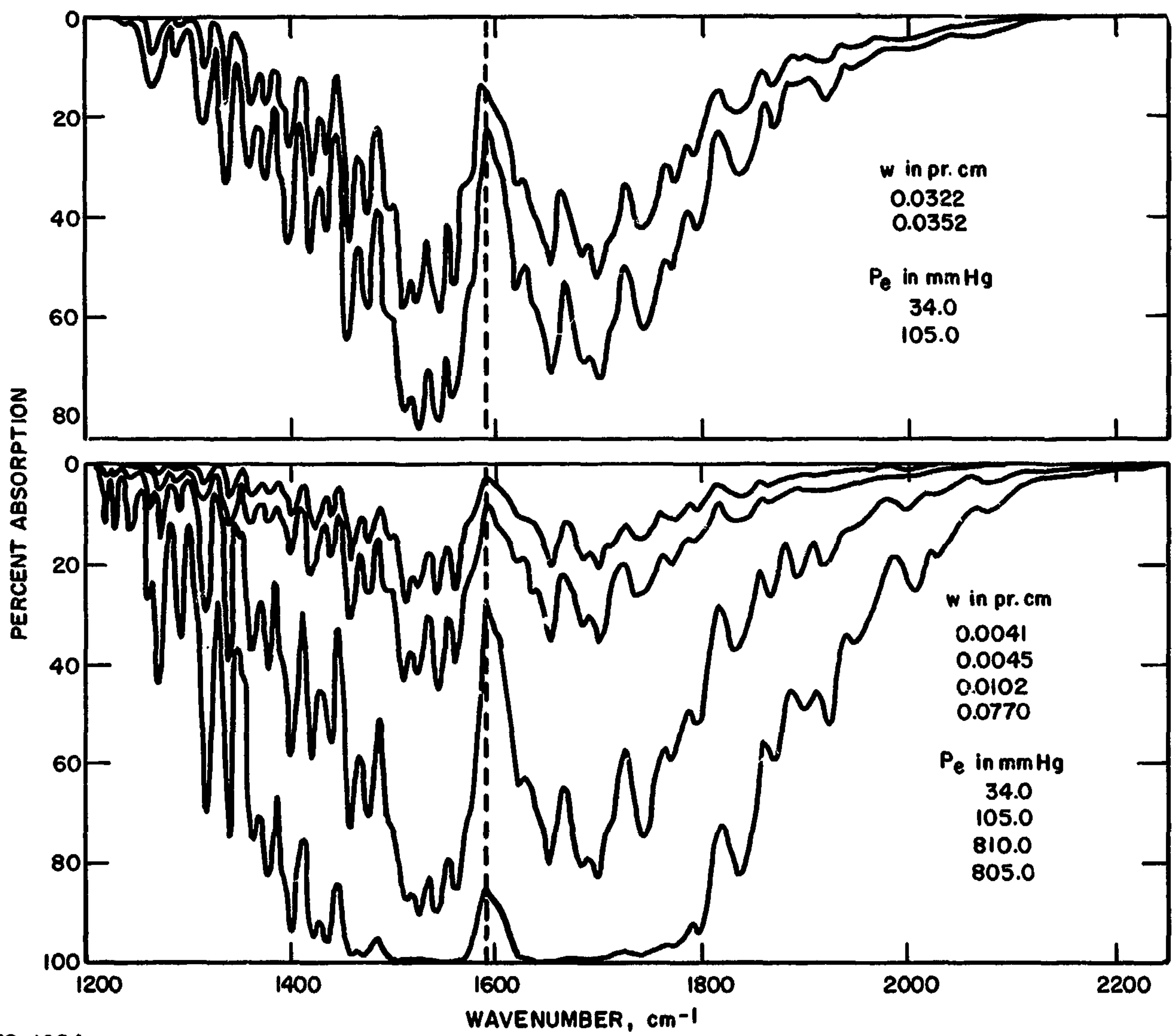

ARCTIC MODEL
PRESSURE, mb (mean)
10
50
100
500
1000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$B\frac{d\tau}{d\ln p}$
1640-1660 cm^{-1}
1880-1900 cm^{-1}
1980-2000 cm^{-1}
78-1079



MIDLATITUDE MODEL
1640 - 1660 cm⁻¹
1880 - 1900 cm⁻¹
1980-2000 cm⁻¹
PRESSURE, mb (mean)
10
50
100
500
1000
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$B \frac{d\tau}{d \ln p}$
78-1080

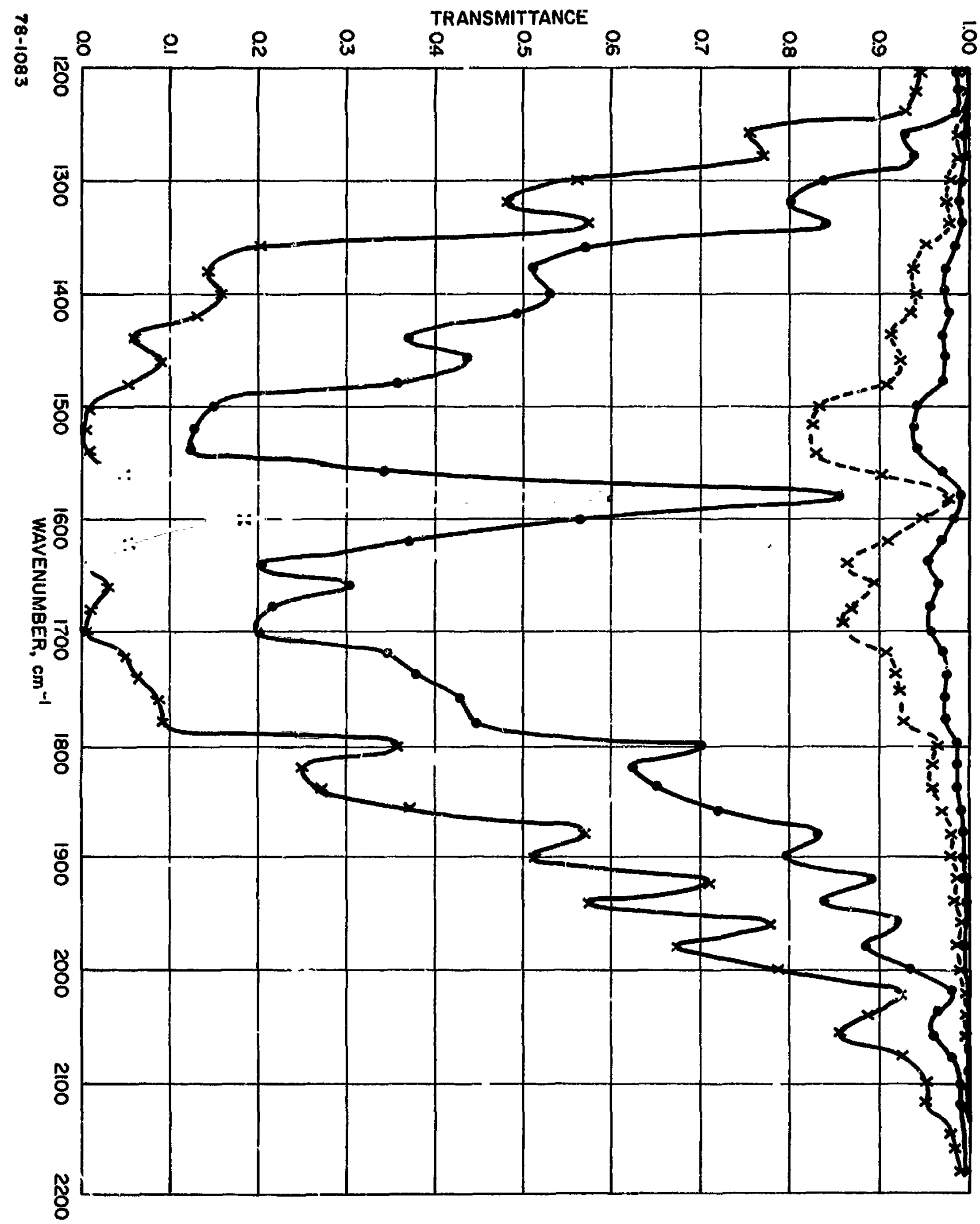

TROPICAL MODEL
1640-1660cm-1
1880-1900 cm-1
1980-2000 cm-1
PRESSURE, mb (mean)
10
50
100
500
1000
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
B dτ/d ln p
78-1081

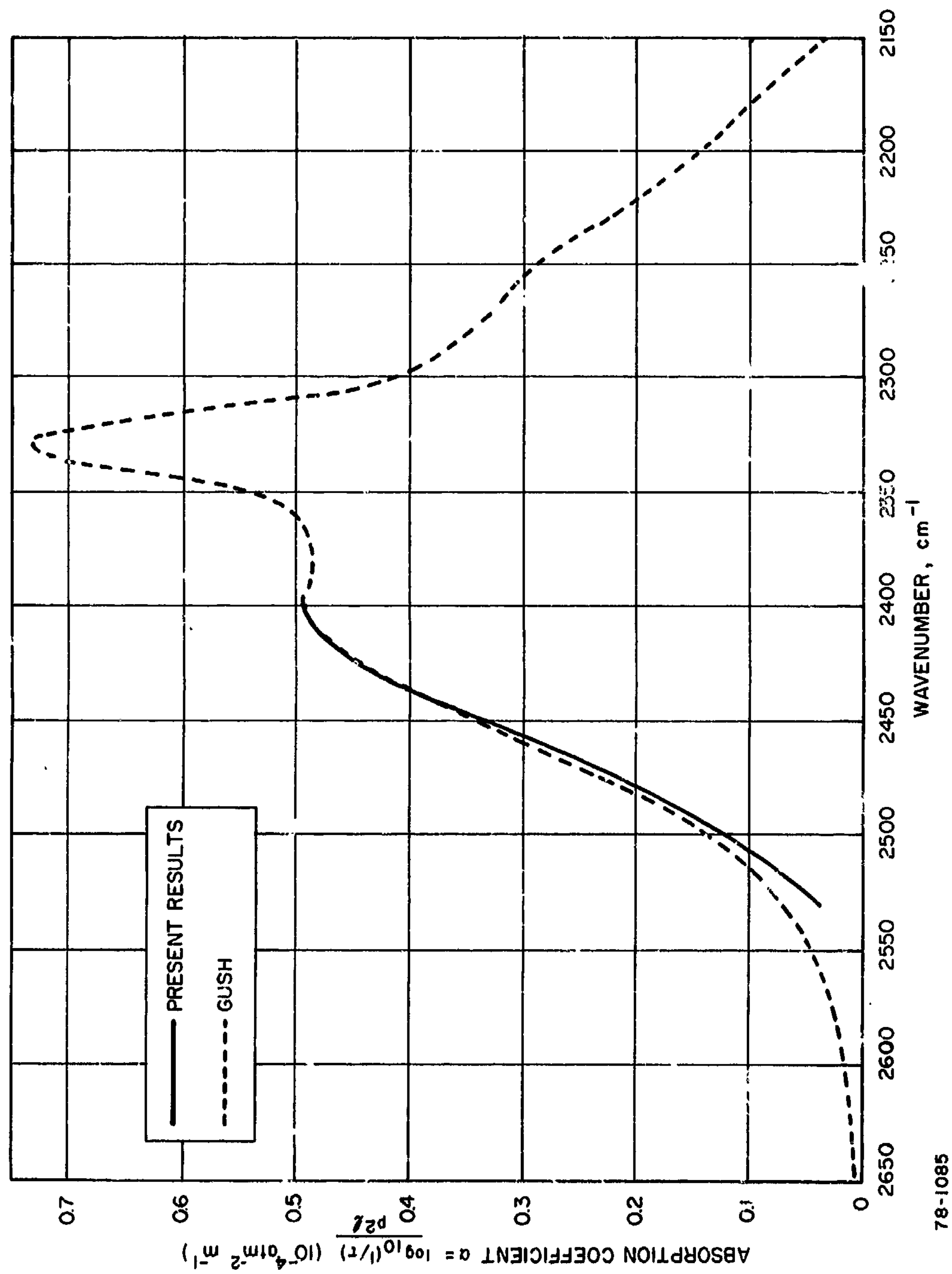

TRANSMITTANCE
1.0
0.8
0.6
0.4
0.2
0.0
2000
2100
2200
2300
2400
WAVENUMBERS, cm^{-1}
ARCTIC MODEL
MIDLATITUDE MODEL
TROPICAL MODEL
78-1082

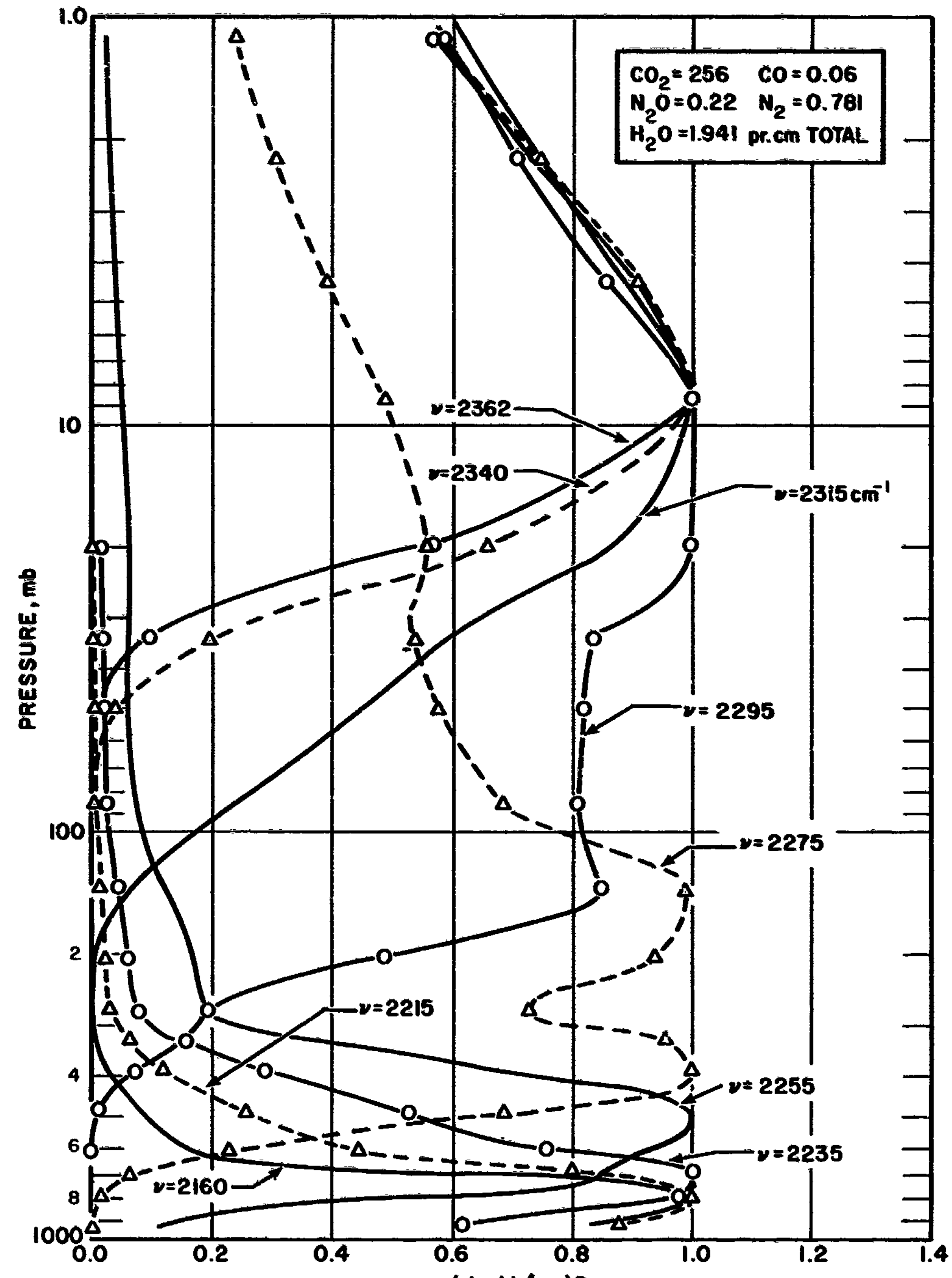


w in pr. cm
0.0322
0.0352
Pe in mmHg
34.0
105.0
w in pr. cm
0.0041
0.0045
0.0102
0.0770
Pe in mmHg
34.0
105.0
810.0
805.0
PERCENT ABSORPTION
WAVENUMBER, cm-1

78-1084

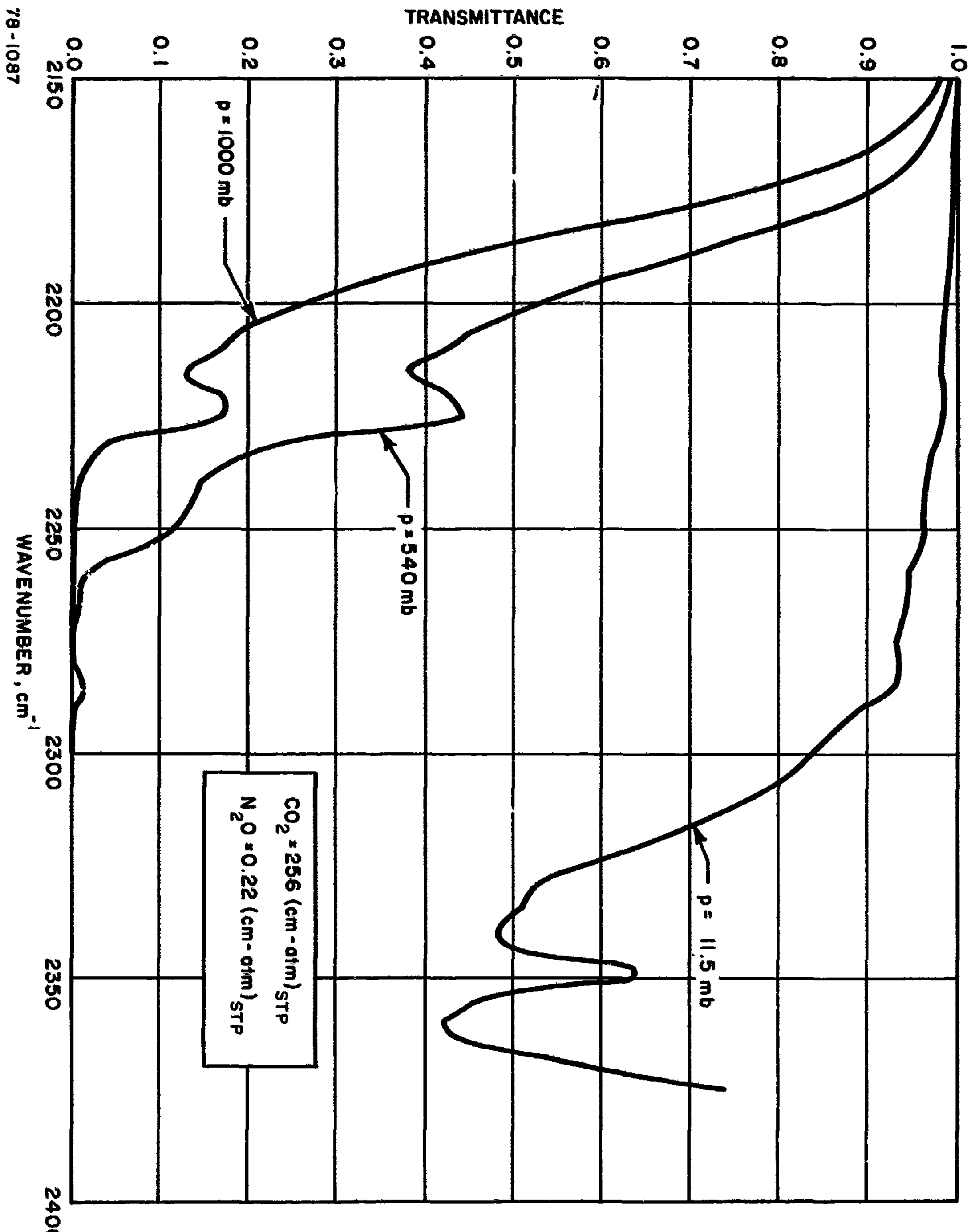

TRANSMITTANCE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.00
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
WAVENUMBER, cm⁻¹
78-1083


PRESENT RESULTS
GUSH
ABSORPTION COEFFICIENT α = log10(I/τ) / ρ²ℓ (10^-4 atm^-2 m^-1)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
2650
2600
2550
2500
2450
2400
2300
2200
2150
WAVENUMBER, cm^-1
78-1085

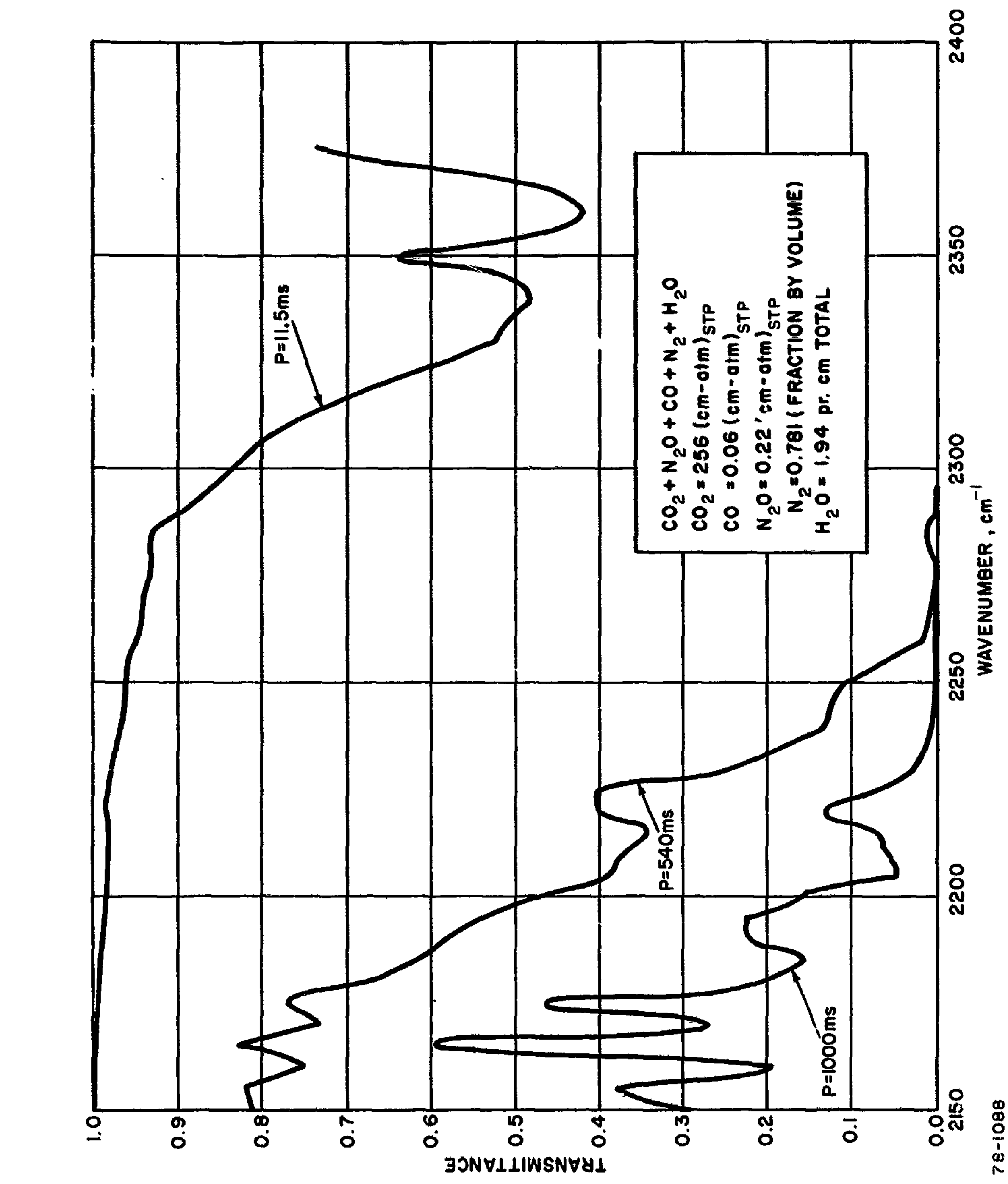


CO_2 = 256 CO = 0.06
N_2O = 0.22 N_2 = 0.781
H_2O = 1.941 pr.cm TOTAL
ν=2362
ν=2340
ν=2315 cm⁻¹
ν= 2295
ν= 2275
ν=2215
ν= 2255
ν= 2235
ν=2160
PRESSURE, mb
(dτ/d ln p)B

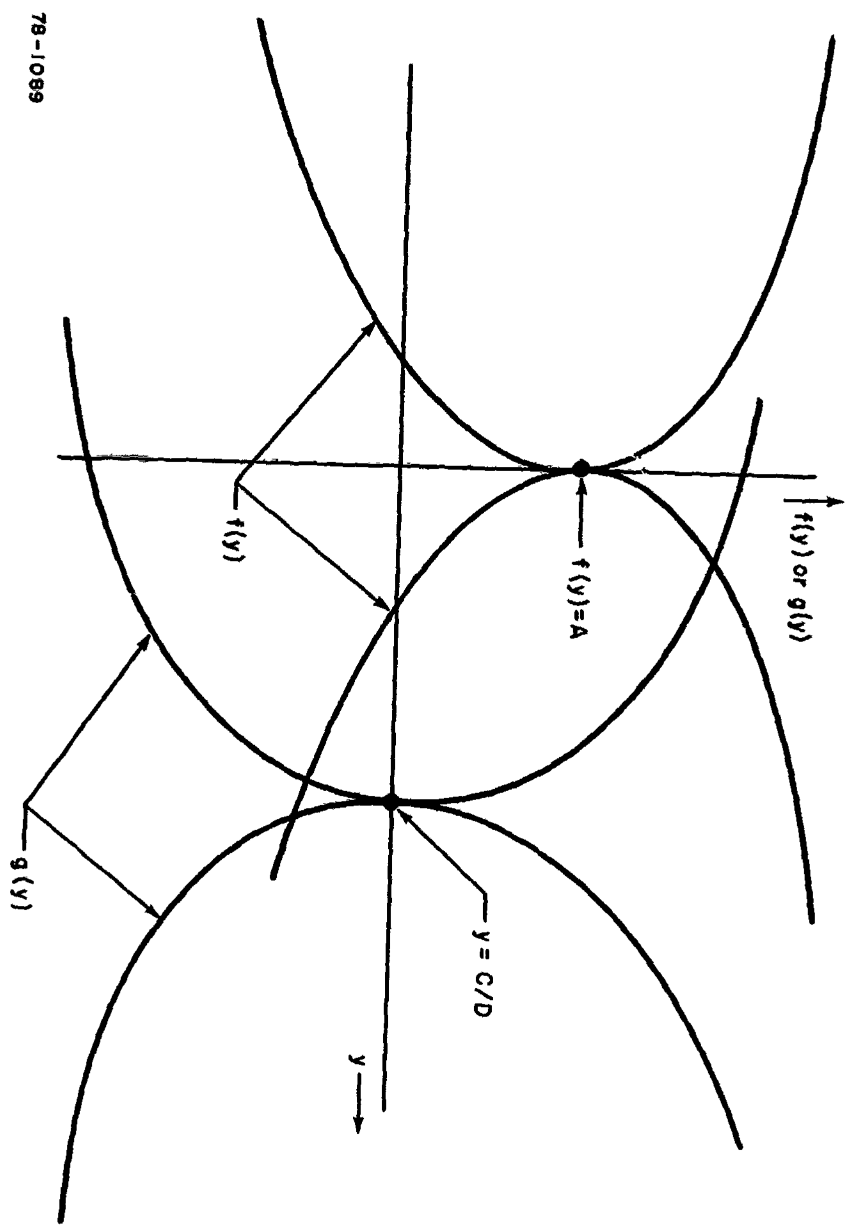
78-1086

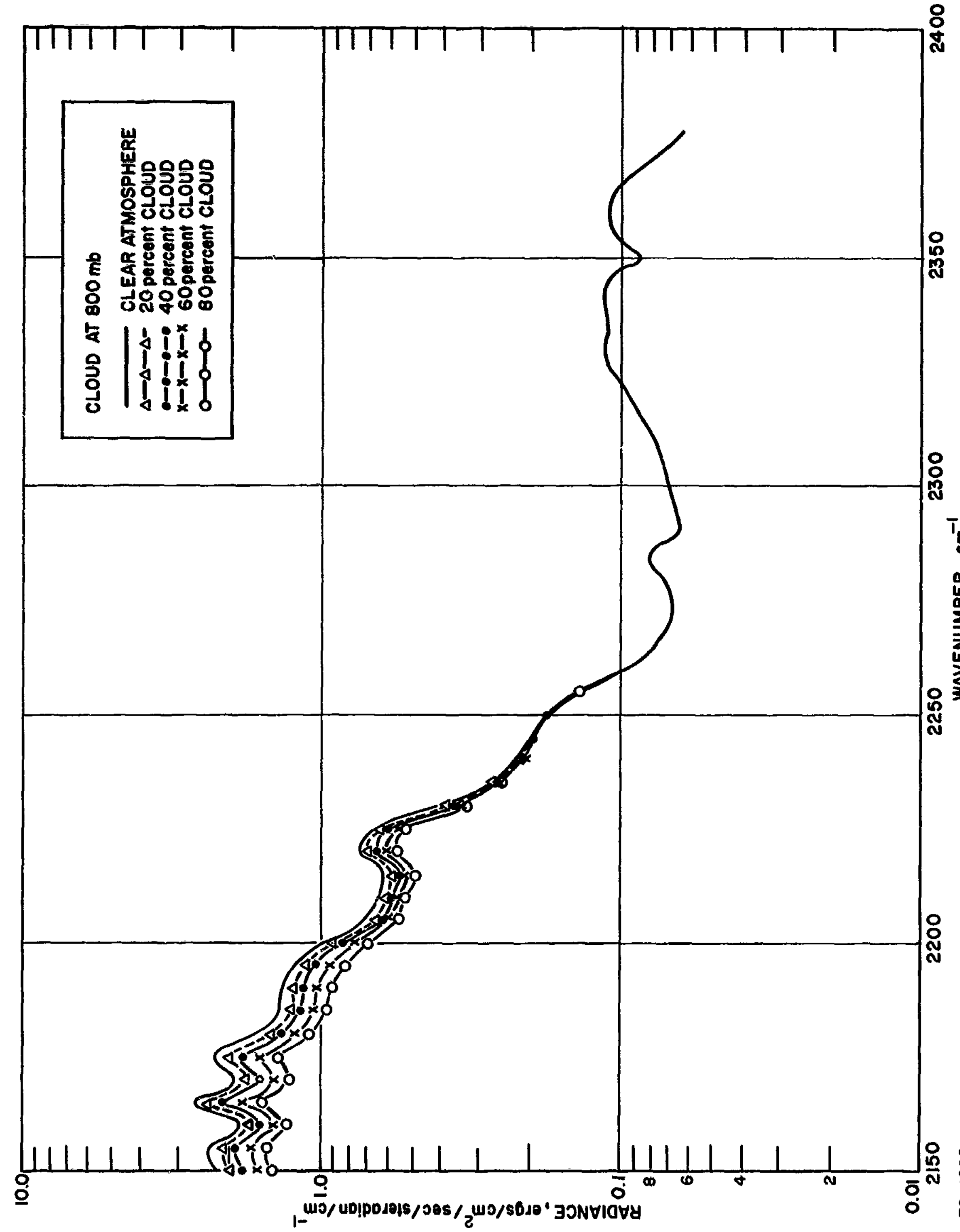


TRANSMITTANCE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
2150
2200
2250
2300
2350
2400
WAVENUMBER, cm^{-1}
p = 1000 mb
p = 540 mb
p = 11.5 mb
CO_2 = 256 (cm-atm)$_{STP}$
N_2O = 0.22 (cm-atm)$_{STP}$
78-1087

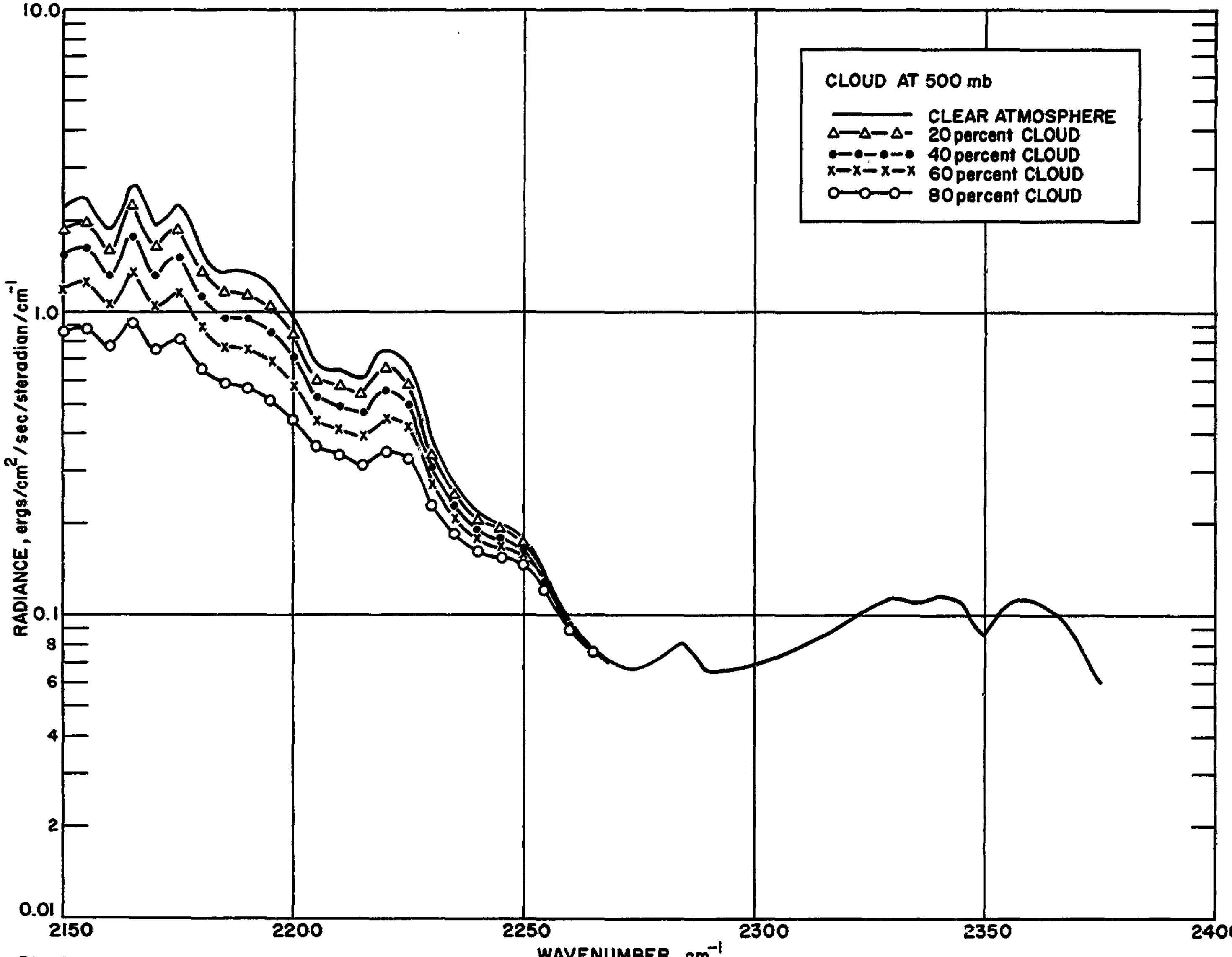


TRANSMITTANCE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2150
2200
2250
2300
2350
2400
WAVENUMBER, cm⁻¹
P=11.5ms
P=540ms
P=1000ms
CO2 + N2O + CO + N2 + H2O
CO2 = 256 (cm-atm)STP
CO = 0.06 (cm-atm)STP
N2O = 0.22 (cm-atm)STP
N2 = 0.781 (FRACTION BY VOLUME)
H2O = 1.94 pr. cm TOTAL
78-1088

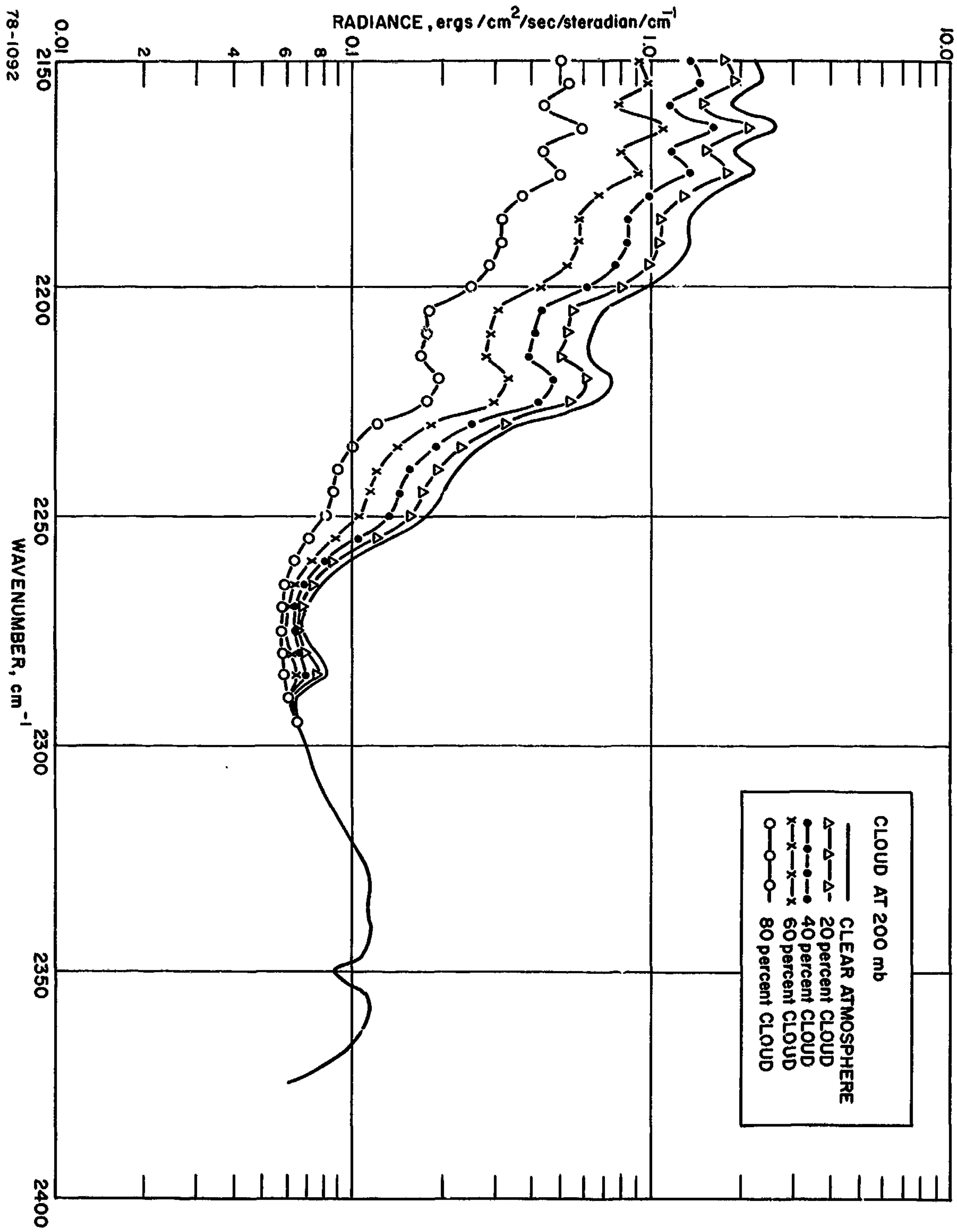

78-1089
f(y)
g(y)
f(y)=A
f(y) or g(y)
y = C/D
y


CLOUD AT 800 mb
CLEAR ATMOSPHERE
20 percent CLOUD
40 percent CLOUD
60percent CLOUD
80percent CLOUD
RADIANCE, ergs/cm^2/sec/steradian/cm^{-1}
WAVENUMBER, cm^{-1}
10.0
1.0
0.1
8
6
4
2
0.01
2150
2200
2250
2300
2350
2400

78-1090


CLOUD AT 500 mb
CLEAR ATMOSPHERE
20 percent CLOUD
40 percent CLOUD
60 percent CLOUD
80 percent CLOUD
RADIANCE, ergs/cm^2/sec/steradian/cm^{-1}
10.0
1.0
0.1
8
6
4
2
0.01
2150
2200
2250
2300
2350
2400
WAVENUMBER, cm^{-1}

78-1091


CLOUD AT 200 mb
CLEAR ATMOSPHERE
20 percent CLOUD
40 percent CLOUD
60 percent CLOUD
80 percent CLOUD
RADIANCE, ergs/cm²/sec/steradian/cm⁻¹
WAVENUMBER, cm⁻¹
78-1092